Title:
Mapping the human brain's cortical-subcortical functional network organization

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ABSTRACT

Understanding complex systems such as the human brain requires characterization of the system's architecture across multiple levels of organization—from neurons, to local circuits, to brain regions, and ultimately large-scale brain networks. Here we focus on characterizing the human brain's comprehensive large-scale network organization, as it provides an overall framework for the organization of all other levels. We leveraged the Human Connectome Project dataset to identify network communities across cortical regions, replicating well-known networks and revealing several novel but robust networks, including a left-lateralized language network. We expanded these cortical networks to subcortex, revealing 288 highly-organized subcortical segments that take part in forming whole-brain functional networks. This whole-brain network atlas—released as an open resource for the neuroscience community—places all brain structures across both cortex and subcortex in a single large-scale functional framework, substantially advancing existing atlases to provide a brain-wide functional network characterization in humans.

INTRODUCTION

Understanding the highly distributed neural computations that underlie cognitive abilities in humans will require a framework that places neural events in the context of overall brain network organization. Several such frameworks have been introduced (Power et al., 2011; Yeo et al., 2011), based on the idea that the brain exhibits a modular functional architecture enabling efficient processing (Bullmore and Sporns, 2009). Consistent with this, distributed clusters of brain regions are strongly functionally interconnected (showing high statistical association between time series), composing distinct functional networks. These functional networks can be detected using resting-state functional connectivity (RSFC) with functional MRI (fMRI), capitalizing on the phenomenon of spontaneous but coherent low-frequency fluctuations of the BOLD (blood-oxygen level dependent) signal. This phenomenon can give insight into the brain's intrinsic functional network organization that likely underlies a host of computations, including higher-order cognition. This intrinsic organization is thought to be functionally relevant since brain activity patterns during rest and task have high overall correspondence (Smith et al., 2009b). Moreover, task-evoked activity flow (the movement of task-evoked activations between brain regions) can be accurately predicted using RSFC, suggesting that resting-state functional networks shape cognitive task activations (Cole et al., 2016). This hypothesis is additionally supported by findings of strong correspondence between resting-state and task-state functional connectivity: Only subtle changes are observed in brain-wide functional connectivity organization during a wide variety of (functionally distinct) tasks and rest (Cole et al., 2014a; Krienen et al., 2014). These findings suggests that, although smaller task-specific changes in cortical organization occur during tasks, the main functional network architecture is already present during rest.

Yet there remains a large knowledge gap in defining an accurate whole-brain network partition, i.e., a neurobiologically-plausible organization of network modules underlying distributed neural computations. While a number of network partitions have been developed (Doucet et al., 2011; Gordon et al., 2016; Laumann et al., 2015), two of the most widely utilized are those by Power et al. (2011) and Yeo et al. (2011). Their widespread impact likely stems from their strong correspondence with well-established primary sensory-motor systems, as well as correspondence with well-replicated co-activation patterns (e.g., frontoparietal co-activations during working memory tasks) in the task fMRI literature (Smith et al., 2009b; Yeo et al., 2015). Both groups used clustering algorithms to identify functional networks based on distributed patterns of high RSFC between brain regions (for Power et al. (2011)) or a grid of cortical surface locations (for Yeo et al. (2011)). Together, they revealed a common brain network organization with bilaterally distributed visual, sensorimotor, default mode, and attention networks. Furthermore, both solutions revealed a task-positive system (the fronto-parietal, dorsal attention and cingulo-opercular networks) and a task-negative system consisting of the default mode network (Fox et al., 2005; Power et al., 2011). These network partitions have proven to be remarkably valuable in elucidating functional brain organization and have provided an initial framework for functional network analyses in a variety of studies, both in health and disease, yielding important new insights in multiple fields of neuroscience (Sporns, 2014).

However, the currently existing network partitions were not able to overcome certain key limitations due to technical and methodological constraints, limiting the obtained precision of network assignments. As the authors themselves highlighted, the use of volumetric data and spherical regions of interest, large voxel sizes and no comprehensive subcortical network

solution could all lead to misrepresentations in final network partitions (Power et al., 2011; Yeo et al., 2011). While these were vital "first generation" network partition attempts, the field of neuroimaging is still rapidly developing (Glasser et al., 2016; Uğurbil et al., 2013), affording leaps in methodological optimization. Consequently, we sought to employ recent major methodological advances in acquisition and analytics to derive a "second generation" unified whole-brain network partition. The expectation was that these improvements in data quality and analysis approach could reveal new insights into the brain's functional organization. Additionally, we sought to develop this improved network partition for use by the neuroscience community, with the goal that it can be used to improve results across a variety of studies investigating human brain function in health and disease. We are also making all of the code and data used to produce our partition publically available, assisting future studies seeking to iteratively improve upon the inevitable technical limits of the present work.

Thus, the goal is not only to provide stronger evidence for previous network assignments but also to create a methodologically-improved "second generation" functional network partition by addressing numerous well-known limitations of earlier partitions. First, as a starting point, we leveraged a recently-developed surface-based cortical parcellation (Glasser et al., 2016), which combined multiple neuroimaging modalities (i.e., myelin mapping, cortical thickness, task fMRI, and RSFC) to drastically improve cortical area assignment. These improvements were driven by strong quantitative convergence across independent MR-based modalities, each with complementary strengths and weaknesses. Second, we used multi-band fMRI data from the Human Connectome Project (Van Essen et al., 2013), allowing for superior spatio-temporal resolution (i.e. simultaneous acquisition of multiple slices at a small voxel size) relative to data used for previous network partitions (Feinberg et al., 2010; Moeller et al., 2010). This substantially increased the spatial and temporal detail of the RSFC estimates and the resulting network partition. Third, we also increased the spatial specificity and anatomical fidelity of the RSFC data by using a high-resolution surface-based analysis. Such surface-based methods yield far superior across-subject alignment of cortical geometry (Anticevic et al., 2008; Glasser et al., 2013) (as opposed to volume-based methods (Craddock et al., 2012; Shen et al., 2013)). This collectively results in less spatial blurring across sulcal boundaries within an individual and superior cross-areal alignment across individuals (Uğurbil et al., 2013).

Building on these methodological advances, a plausible network partition should have a neurobiologically plausible number of networks, including well-known functional systems (Mesulam, 1998; Ryali et al., 2012; Stark et al., 2008) as well as subcortical components (Buckner et al., 2011; Choi et al., 2012). For example, although many known systems were already included in previous network partitions, there was no clear assignment of a language network (at least in the "first generation" Power and Yeo network partitions), even though there is ample evidence in the literature for the existence of a distributed language system in humans (Broca, 1861; Hampson et al., 2002; Wernicke, 1874), and perhaps even a homologous network in non-human primates (Mantini et al., 2013). In fact, this was a major knowledge gap that was partially addressed by the Glasser cortical parcellation—namely identification of putatively novel language-related cortical regions, with clear but heretofore undefined boundaries (Glasser et al., 2016). Therefore, we explicitly tested the hypothesis that a methodologically improved and neurobiologically-plausible network solution should yield a brain-wide language network based on RSFC graphs. In turn, such a language network should pass the test of mapping onto language-relevant computations based on independent overlap with task-evoked signals during language processing.

We additionally sought to overcome a key technical limitation of previously-developed network partitions in which there was high uncertainty about the network assignment of the ventral cortical surface. This uncertainty stems from sinus-related MRI dropout (due to magnetic field inhomogeneities) in these regions. The use of multiband fMRI data not only provides a higher signal-to-noise ratio (SNR) due to higher temporal resolution, but also affords less dropout due to higher spatial resolution (Merboldt et al., 2000; Smith et al., 2013). We hypothesized that this would allow for network assignments for regions in MRI dropout areas such as orbitofrontal cortex, for which no clear network assignment currently exists.

We also sought a highly principled approach to defining networks that would be both reproducible and that could be built on by future efforts to refine network definitions even further. This required dealing with two challenges that previously-developed network partitions faced. First, we made sure that each step taken toward producing the network partition was described in detail (and in publically-available code), allowing for precise testing for replication. Second, we acknowledged that the brain can be considered hierarchically, deciding to identify network structure at a particular level of organization: the same level of organization as primary sensory-motor systems. This involved calibrating our community detection algorithm to identify primary visual, auditory, and somatomotor systems. This calibration may have resulted in merging networks that may be statistically possible to fractionate with different parameters—such as shown by the 7-network vs. 17-network solutions by Yeo et al. (2011). However, as opposed to optimizing for a select statistical parameter, here we identified the level of organization consistent with the spatial resolution of primary sensory-motor systems.

Finally, a fundamental knowledge gap in the field is a lack of a unified whole-brain network partition, which includes all of cortex and subcortex. Prior work utilized the cortical network assignment to delineate network partitions for the striatum (Choi et al., 2012) and the cerebellum (Buckner et al., 2011), which revealed a shared functional topography between these large anatomical structures (i.e., cortex, striatum, and the cerebellum). However, no study has extended this approach simultaneously across the striatum, cerebellum, thalamus and the brainstem in a common framework. More generally, there is currently no whole-brain partition of the human brain that capitalizes on the aforementioned advances of more precise cortical mapping and that concurrently provides a comprehensive subcortical network mapping. To address this major knowledge gap, we produced a comprehensive network assignment of all subcortical voxels, which we mapped using a connectivity-based clustering analysis building on our cortical network solution. Functional interconnections between subcortical units (voxels) and cortical regions thus help clarify the functional organization of subcortical structures in the context of cortical brain systems.

The resulting brain-wide network solution provides three key innovations: i) Methodologically it respects the geometry of cortical convolutions (i.e is explicitly surface-based) while providing a unified whole-brain cortical-subcortical solution across hundreds of human participants. ii) It provides a discovery of new functional networks while also mapping a brain-wide language network in humans. iii) This network partition, which we release as part of this report, will be of substantial benefit for future studies both neurobiologically and statistically, providing a grounded framework for analysis of neuroimaging data across large-scale systems in health and disease. Collectively, while we anticipate future improvements of the provided version 1.0, this constitutes the most accurate estimate of whole-brain functional network organization in humans to date.

METHODS

Experimental Model and Subject Details

Dataset

The analyzed dataset consisted of 337 healthy volunteers from the publicly available Washington University – Minnesota (WU-Min) Human Connectome Project (HCP) data (Van Essen et al., 2013). Participants were recruited from Washington University (St. Louis, MO) and the surrounding area. We selected participants from the "S1200" release of the HCP who had no family relations, resulting in 337 participants being included in our analyses. The dataset contains resting-state fMRI data from 180 females and 157 males, with age range 22-37 (mean age=28.6, SD=3.7), 90% right-handed. Informed consent was obtained from each participant as directed by the institutional review board at Washington University at St. Louis. All analyses were approved by the Yale and Rutgers IRBs. In total, four resting-state BOLD sessions were collected for each participant, which were used for functional network identification. Participants also performed a variety of tasks with fMRI (Barch et al., 2013). The analyses here focused on the data obtained from the language processing task.

Method Details

Data Acquisition

Whole-brain echo-planar imaging acquisitions were measured with a 32 channel head coil on a modified 3T Siemens Skyra (Connectome Skyra) at WashU with time to repetition (TR)=720ms, time to echo (TE)=33.1ms, flip angle=52, bandwidth=2,290 Hz/pixel, in-plane field of view (FOV)=208×180mm, 72 slices, and 2.0mm isotropic voxels, with a multi-band acceleration factor of 8 (Uğurbil et al., 2013). Data were collected over 2 days. On each day 29 min of rest (eyes open with fixation on a cross-hair) BOLD data across two runs were collected (56 min total), followed by 30 min of task fMRI data collection (60 min total). The two 14.5-minute resting-state BOLD runs that were collected on the same day were acquired with opposite phase-encoding directions (L/R & R/L). Complete parameters and acquisition details for the HCP dataset were reported by Smith et al. (2013). Task-based imaging details are documented in detail by Barch et al. (2013). Each of seven HCP tasks was completed over two consecutive fMRI runs. In this report we focused on the language processing task data ("LANGUAGE story") to test the performance of our partition. The acquisition parameters were similar to the resting-state BOLD sessions and consisted of two runs collected on the same day acquired with opposite phase-encoding directions (L/R & R/L). Structural scans with the following parameters were also collected: T1-weighted (0.7 mm isotropic resolution, TR=2400ms, TE=2.14ms, flip angle=8, in-plane field of view=224×224) and T2-weighted (0.7 mm isotropic resolution, TR=3200ms, TE=565ms, variable flip angle, in-plane field of view=224×224). Complete details of all HCP acquisition can be found online (https://www.humanconnectome.org/storage/app/media/documentation/s900/HCP_S900_Release_Reference_Manual.pdf).

Quantification and Statistical Analysis

The methodological workflows for creating cortical and subcortical network partitions are displayed in Fig. 2a and Fig. 3a. In summary, for both partitions, data were first preprocessed via HCP convention, followed by calculation of an average FC matrix (parcel-to-parcel for cortical data or parcel-to-voxel for subcortical data). A cortical partition was then calculated using a clustering algorithm and several pre-determined (hard and soft) criteria, followed by a quantitative evaluation of network solutions. The initial cortical assignment steps are described in detail in forthcoming sections. In turn, this cortical network partition was then used to calculate subcortical network assignment. Here the subcortical voxel was assigned to the cortical network with which is was most highly correlated on average, followed by several quality assurance steps described below.

Resting-State fMRI Preprocessing

Preprocessing consisted of the following steps, which closely followed the steps advanced by the HCP consortium: i) The 'minimal preprocessing' approach outlined by Glasser and colleagues (Glasser et al., 2013), which involved intensity normalization, phase-encoding direction unwarping, motion correction, and spatial normalization to a standard template (Glasser et al., 2016) MSMAll, Angular Deviation Penalty (ADP) version; (Glasser et al., 2016); ii) High-pass filtering (0.009Hz); iii) ICA-FIX for artifact removal (Salimi-Khorshidi et al., 2014). The final 'minimally preprocessed' BOLD data was represented in the Connectivity Informatics Technology Initiative (CIFTI) file format, which combines surface-based data representation for cortex and volume-based data for subcortex gray matter locations (i.e. 'grayordinates'). The CIFTI grayordinate BOLD time series were in turn used for subsequent analysis. Additional analyses were performed with Workbench v1.2.3 and Matlab 2014b (The Mathworks). To remove any potential artifact at the onset/offset of each new run, the first 100 frames were removed from every BOLD run for each subject. Subsequently, BOLD runs were concatenated in order of acquisition (resting-state fMRI runs 2-1-4-3, R/L first, then L/R) following removal of the mean of each run from each time series. We began by focusing on cortical data, with a subsequent extension of the identified network partition to subcortical data.

Resting-State Cortical FC Matrices

To sample data at the regional level, we used a recently-developed cortical parcellation (Glasser et al., 2016), which contains 180 symmetric cortical parcels per hemisphere. This parcellation is defined in terms of surface vertices and is shown to be substantially more accurate than any prior parcellations due to the consistency of areal borders between data from different modalities and an accurate representation of cortical geometry for each subject via the CIFTI file format (Glasser et al., 2016). For each subject, BOLD time courses were extracted from the 360 independently identified parcels using Workbench. An average BOLD time course for each parcel was calculated by averaging across all vertices/grayordinates within that region. Subsequently, RSFC between each pair of parcels was calculated for each subject using Pearson correlation. A functional connectivity matrix for N regions is defined as the N×N matrix M, where M(i, j) contains the Pearson correlation of the time courses between region i and region j. In this way, a 360 x 360 RSFC matrix was formed for each subject. Finally, a single group average RSFC matrix was formed by averaging across all subjects in the cohort, and setting the diagonal to zero.

Network Detection Using Clustering Algorithm: Louvain Clustering Algorithm

We sought to establish a neurobiologically principled approach to community detection driven by minimal assumptions and devoid of qualitative decisions. Our approach was based roughly on (Cole et al., 2014a), which was adapted from methods proposed by Power et al. 2011. We identified three "hard" criteria for what we considered a principled network partition solution, with two additional "soft" criteria.

The hard criteria included: i) separation of primary sensory-motor cortical networks (visual, auditory, and somatomotor) from all other networks. This criterion is based on unequivocal evidence supporting the existence of these as functionally distinct sensory and motor systems in the human brain. If a network partition is to be neurobiologically-grounded it should pass this standard. Note that previous functional network partitions of the human brain have had difficulty separating auditory cortex from somatomotor cortex (Yeo et al., 2011). Consistent with these prior observations, auditory cortex tended to be merged with somatomotor cortex for most of the tested algorithms and algorithm parameters. ii) high stability (similarity of network partitions) across nearby parameters in the network detection algorithm. This criterion served as a heuristic for detecting likely low-noise-influenced partition solutions. iii) High modularity (high within-network connectivity relative to between-network connectivity). This final criterion is implicit in community detection algorithms, which attempt to optimize network partitions for modularity. However, we included this as an additional explicit quantitative criterion to ensure that optimizing for other criteria did not reduce modularity substantially. A putative network solution had to meet the three "hard" criteria to even be considered.

The two "soft" criteria for network partition selection included: i) We optimized the network partition with the constraint that the number of large-scale functional networks should be roughly similar to the number of networks identified in previous functional network solutions using RSFC data (Power et al., 2011; Yeo et al., 2011). These ranged from 7 networks to 17. Importantly, this number of networks is largely consistent with the number of networks typically described in the human fMRI task activation literature, as well as the number of large-scale systems described in the animal neuroscience literature. Put differently, while statistically possible, a network partition with an order of magnitude finer granularity (e.g. >100 sub-networks) would not be considered. ii) We sought a network partition with non-primary networks (other than primary sensory-motor cortical networks that were part of the "hard" criteria our partition, e.g., frontoparietal cognitive control network, default-mode network) qualitatively similar to those that were previously identified using RSFC and fMRI task activations (Power et al., 2011; Smith et al., 2009b; Yeo et al., 2011, 2015). Critically, these two soft criteria had only minimal influence on the finalized partition, since only the hard criteria were used to identify that partition. Instead, these criteria were more important for assessing community detection algorithms, wherein we determined if a given algorithm was providing results (without full parameter optimization) largely consistent with the RSFC, fMRI task activation, and animal neuroscience literatures. Notably, RSFC, fMRI task activation, and animal neuroscience all have weaknesses that are largely non-overlapping (e.g., movement confounds RSFC more than fMRI task activations), such that considering constraints across these sources of evidence strengthens our conclusions.

We started by applying the described criteria across a variety of community detection algorithms. Among the different algorithms explored were OSLOM (Lancichinetti et al., 2011), k-means, hierarchical clustering, SpeakEasy (Gaiteri et al., 2015), InfoMap (Rosvall and Bergstrom, 2008), and the Louvain algorithm (Blondel et al., 2008). Ultimately, the Louvain clustering algorithm method was selected for its ability to easily adjust the resolution of

community clustering (i.e., the tendency for smaller communities to be detected), which allowed for optimization of the community clustering based on the "hard" criteria described above. This algorithm was also selected because produced solutions exhibited evidence in support of the "soft" criteria—a number of communities that were broadly similar in number and configuration to what was found in previous RSFC studies and in meta-analyses of fMRI task data. Briefly, the Louvain algorithm works in the following way: First, it searches for small communities by optimizing local modularity. Second, it combines small communities into nodes and builds a new network. Finally, this process is iteratively repeated until modularity changes minimally. Ultimately, as with other community detection algorithms, the Louvain algorithm attempts to optimize for the strength of within-community connections relative to the strength of between-community connections (i.e., modularity) (Blondel et al., 2008).

Iterative Louvain Clustering and Cluster Consolidation

We started by using a gamma (partition resolution) parameter of 1.0, since this is used as a standard resolution for the Louvain algorithm. Initially, this parameter yielded a network partition with the auditory network merged with the somatomotor network, violating one of our "hard" criteria. We therefore initiated a search over gamma values based on the hard criteria described above. As a randomly seeded algorithm dependent on optimization, it is possible that one iteration of Louvain would fail to identify the global (or a near-global) maximum for community modularity. To address this issue, we ran 1000 randomly-initialized iterations of Louvain for each gamma value (range of 1.2 to 1.4 in increments of 0.005), using the Rutgers-Newark supercomputing cluster (Newark Massive Memory Machine). We assessed partition quality by quantifying the stability of the partition solution at each gamma value. Stability estimates were computed as the z-rand partition similarity (Traud et al., 2011) averaged across all other iterations for a given gamma value. Thus, if the same parcels were more consistently assigned to the same networks across randomly-initialized iterations for a given gamma value then there would be a higher z-rand score for that gamma value, indicating higher partition stability. The randomly-initialized iteration with the highest average z-rand (i.e., highest mean similarity with all other iterations) was selected as the representative partition solution for that gamma value. Z-rand scores and a calculated modularity score for each generated partition were subsequently examined in the gamma stability analysis described below.

Partition Stability Calculation

For each gamma value, z-rand scores and modularity scores across all iterations were averaged to find representative z-rand and modularity values. Next, each mean z-rand score (quantifying partition stability across 1000 iterations) was multiplied by its corresponding modularity score to find a modularity-weighted z-rand score. The gamma value corresponding to the peak of the modularity-weighted z-rand score plot—constrained by the criterion of finding a plausible number of networks including primary sensory/motor networks—was selected as the most stable and maximally modular solution (see **Fig. 2b**). The partition corresponding to this gamma value was further evaluated for validity and stability across a number of metrics detailed below.

Functional Network Validation and Quality Assessment for the Cortical Network Partition

To test the reliability of our network partition (in a distinct manner from the gamma stability analysis), we conducted an independent split-half validation analysis across two randomly selected subsamples of participants. The network detection algorithm was repeated with the same

gamma value (1.295) that provided the initial partition solution (based on separation of sensory-motor systems, optimal modularity, and gamma stability), but now with two separate subsets of the data (N=168 and N=169) consisting of demographically matched subjects (see Results section for details on these matched data subsets).

To further quantitatively assess the final cortical network partition and validate the parcel assignments, we used several additional measures. First, a network assignment confidence score was calculated for each region to express the certainty with which that region could be assigned to a particular network (Wang et al., 2015). This confidence score was computed as the ratio between the assigned network's correlation value and the out-of-network correlation values for a region *i*:

$$C_i = \frac{\sum r_{s\,i,j}}{n_j} - \frac{\sum r_{s\,i,k}}{n_k}$$

where C_i is the network assignment confidence score for region *i* (one of 360 brain regions), $r_{s\,i,j}$ is the Spearman correlation coefficient between the RSFC patterns of region i and region j in the same network, n_j is the total number of other regions in regions i's network, $r_{s\,i,k}$ is the Spearman correlation coefficient between RSFC patterns of region i and region k outside of regions i's network, and n_k is the total number of regions outside region i's network. If a region's RSFC pattern is very similar to that of the other regions in its assigned network, the confidence score will be high, but if it is also similar to other networks, the confidence score will be lower.

Second, in addition to these network assignment confidence scores, we calculated signal-to-noise ratio (SNR) and participation coefficient (Rubinov and Sporns, 2010) (https://sites.google.com/site/bctnet/measures/list), and correlated these measures to assess whether our network assignment results were affected by SNR (i.e. lower functional connectivity in dropout regions).

Third, RSFC pattern asymmetry was calculated to see how similar a region's or network's RSFC pattern was to that region's homologue on the other hemisphere. For each subject, we correlated each region's (unilateral) RSFC pattern with that of its homologue (as identified by (Glasser et al., 2016)), and subtracted this value from 1. We subsequently averaged these RSFC pattern asymmetries by network. Finally, scores were averaged across subjects.

Fourth, a measure of inter-subject connectivity variability was used to indicate how similar a region's functional connectivity pattern is across subjects. To calculate a region's inter-subject connectivity variability, the rank correlation for each subject's RSFC pattern for a given region with all other subjects was calculated, resulting in a 337 x 337 (number of subjects X number of subjects) connectivity matrix. Averaging all values in this matrix to generate a mean pairwise similarity score "S" for each region, and subtracting this score from 1, resulted in a region's inter-subject connectivity variability score (1-S).

Once these quality metrics were calculated, each parcel was assessed for reassignment (i.e. assigning a parcel to a different network than the one resulting from the Louvain clustering algorithm, based on quantitative assessment of its original assignment). We reassigned parcels if the reassignment increased their confidence scores. Reassignment was applied for only three of the 360 cortical regions. Two left hemisphere DMN regions (regions 26 and 75) were re-assigned to LAN, and one left hemisphere LAN region (region 135) was re-assigned to VMM (due to this resulting in higher confidence scores for all three regions). The left hemisphere LAN region (region 135) also failed to replicate on the split-half test, further indicating a poor initial assignment. The reported quality metrics for the partition were recalculated after reassignment of

those three regions.

Subcortical Network Assignment

Once the cortical network partition was finalized, the subcortical assignment followed. To assign networks to subcortical structures, FC matrices were first created for each subject containing the correlations between the 360 cortical parcels and 31870 grayordinates covering the entire subcortical CIFTI space. The group FC matrix was then calculated by averaging Fisher's z-transformed Pearson correlation values across subjects. Next, the FC of each subcortical grayordinate was averaged across all parcels in each cortical network and the grayordinate was assigned to the network with the highest mean Fisher's z-transformed correlation. This approach was chosen to account for the differences in cortical network size, as an unweighted approach would result in a bias towards networks with more cortical parcels.

To account for any signal bleed-over from the adjacent cerebral cortex or partial volume effects in the cerebellum, we removed cerebellar voxels within 2mm of the cortex from the initial network assignment (**Supplemental Figure S1**). These effects were not prominent in other subcortical structures. We additionally performed cleanup steps of the raw network assignment due to low confidence in making inferences from very small clusters in fMRI data. To achieve cleanup, we removed isolated single-voxel parcels that did not share a network assignment with any adjacent voxels, and parcels of size 2-4 voxels that did not have a counterpart with the same network assignment within a 2mm radius in the contralateral hemisphere. The total number of voxels removed by this process and the map of removed voxels are given in **Supplemental Figure S2**. We also searched for 5-voxel parcels that would be removed under the same criteria. The difference achieved with the 5-voxel criteria was trivial. An additional 55 voxels, or 0.17% of the total subcortex, was flagged in the 5-voxel version (**Supplemental Figure S2**), suggesting that the 4-voxel version was already fairly stable. To provide a complete functional atlas of the entire subcortical space, we used nearest-neighbour interpolation to reassign the voxels removed from network assignment in the previous steps. Lastly, parcels which shared a corner and had a continuous contralateral counterpart were combined.

Evaluating the Subcortical Network Assignment

The stability of the subcortical network assignment was tested using a split-half validation analysis, similar to the procedure performed for the cortical network partition. The same network assignment steps described above were performed independently for two separate subsets (N=168 and N=169) consisting of matched subjects (**Fig. 3A-B**). To quantitatively compare the discovery and replication solutions, the proportion of voxels which were assigned to the same network in both solutions was computed. This was done before and after the described cleanup steps were performed (**Fig. 3E-D**). The proportion of voxels expected to overlap by chance in both solutions was calculated for each network, by using the hypergeometric test for proportions given the total number of voxels in the network and the total number of all voxels in the subcortex. 95% confidence intervals for chance were calculated with the Clopper-Pearson method.

Additionally, the asymmetry of the subcortical partition was evaluated. Because the network assignment for the subcortex was computed on the voxel level, rather than the parcel level as with the cortex, the asymmetry was also computed voxelwise. A homologous pair of voxels was defined to be equally displaced from the midline (y-axis) along the x-axis. Observed symmetry was computed as the proportion of voxels in each subcortical network for which the

homologous voxel was assigned to a different network (**Fig. 5E**). Chance asymmetry was calculated as the proportion of voxels in each network that would be expected to overlap between left and right hemispheres if the voxels were randomly assigned, given the number of voxels in the network and the total number of voxels in the subcortex. Additionally, the proportion of each subcortical network in the left and right hemispheres was computed (**Fig. 5F**). Because anatomical connections to and from the cerebellum cross the midline at the level of the pons (van Baarsen et al., 2016) and functional representation (e.g. of somatotopic maps) is mirrored relative to the rest of the brain, the left and right cerebellar hemispheres were exchanged in this analysis.

Subcortical Network Assignment of Data with Global Signal Regression

We also computed a version of the subcortical network assignment using fMRI data with global signal regression (GSR). GSR was performed by regressing the global mean signal from each resting-state fMRI run during preprocessing for each subject. We then computed the network assignment for subcortical voxels using the same procedure as described above ("Subcortical Network Assignment"). The similarity between the two versions was quantified by calculating the proportion of each network in the original partition that was replicated in the version with GSR data (see **Supplemental Figure S4**). Chance overlap was calculated using the hypergeometric test, as described above ("Evaluating the Subcortical Network Assignment").

Task Activation fMRI

Briefly, the language processing task consisted of two runs, each with 4 blocks of a 'LANGUAGE' processing task, which consisted of three components: (i) Auditory sentence presentation with detection of semantic, syntactic and pragmatic violations; (ii) auditory story presentation with comprehension questions; (iii) Math problems that involved sets of arithmetic problems and response periods. Both the 'Story' and 'Math' trials of the LANGUAGE task were presented auditorily and participants chose one of two answers by pushing a button. Further details concerning the LANGUAGE task have been previously described in full by Barch and colleagues (Barch et al., 2013; Binder et al., 2011). Notably, Glasser and colleagues (2016) demonstrated that Area 55b, defined through multi-modal parcellation, was robustly activated in the 'Story versus Baseline' task contrast from the HCP's 'LANGUAGE' task. Here we leveraged that contrast to validate the discovery of the language system. Specifically, task-evoked signal for the LANGUAGE task was computed by fitting a general linear model (GLM) to preprocessed BOLD time series data. Two predictors were included in the model, for the 'Story' and 'Math' blocks respectively. Each block was approximately 30s in length and the sustained activity across each block was modeled (using the Boynton hemodynamic response function (Boynton et al., 1996)). In turn, three unique contrasts were computed for the LANGUAGE task: i) Story versus Baseline, ii) Math versus Baseline, and iii) Story versus Math. Here we focused on the 'Story versus Baseline' contrast, as reported by (Glasser et al., 2016).

Visualizations

All visualizations were produced using Connectome Workbench using the CIFTI format, which combines surface data for cortex with volume data for subcortex. To convert a 360-element partition vector (cortex) into a CIFTI file, the following steps were taken:

1. For each hemisphere, a template 32k vertex CIFTI surface map file was loaded, where

each vertex was labeled with its corresponding parcel label from the Glasser parcels.

2. Each parcel label was replaced with its corresponding network label from the 360-element partition vector.
3. Step 2 was repeated for the opposite hemisphere.
4. Results were saved as a func.gii file for visualization in Connectome Workbench.
5. (Optional) Use the wb_command method *–metric-label-import* to convert the metric file into a label file for customized color options.

Data and Software Availability

Data, software, and the network partition are available upon request. They will be publicly released upon completion of peer review.

RESULTS

Cortical Network Partition

Here we build on the hypothesis that the human brain is a complex dynamical computational system with multiple levels of organization, each level building on the next. We therefore sought to identify the brain's large-scale functional network organization based on clusters of functionally-defined cortical regions—the likely next-lowest level of organization (Felleman and Van Essen, 1991; Glasser et al., 2016; Van Essen and Glasser, 2014). Importantly, higher levels of organization are built from the units at lower levels. Consequently, increased accuracy in mapping brain regions (lower level) may yield more accurate large-scale brain networks (higher level). We therefore quantified functional networks based on regions recently identified via convergence across multiple functional and structural criteria (Glasser et al., 2016), increasing confidence in their accuracy. This yielded a cortical network organization (**Fig. 1A and Fig. 1C**) largely consistent with known and recently-identified functional networks, along with several previously-unidentified but robust networks.

Figure 1

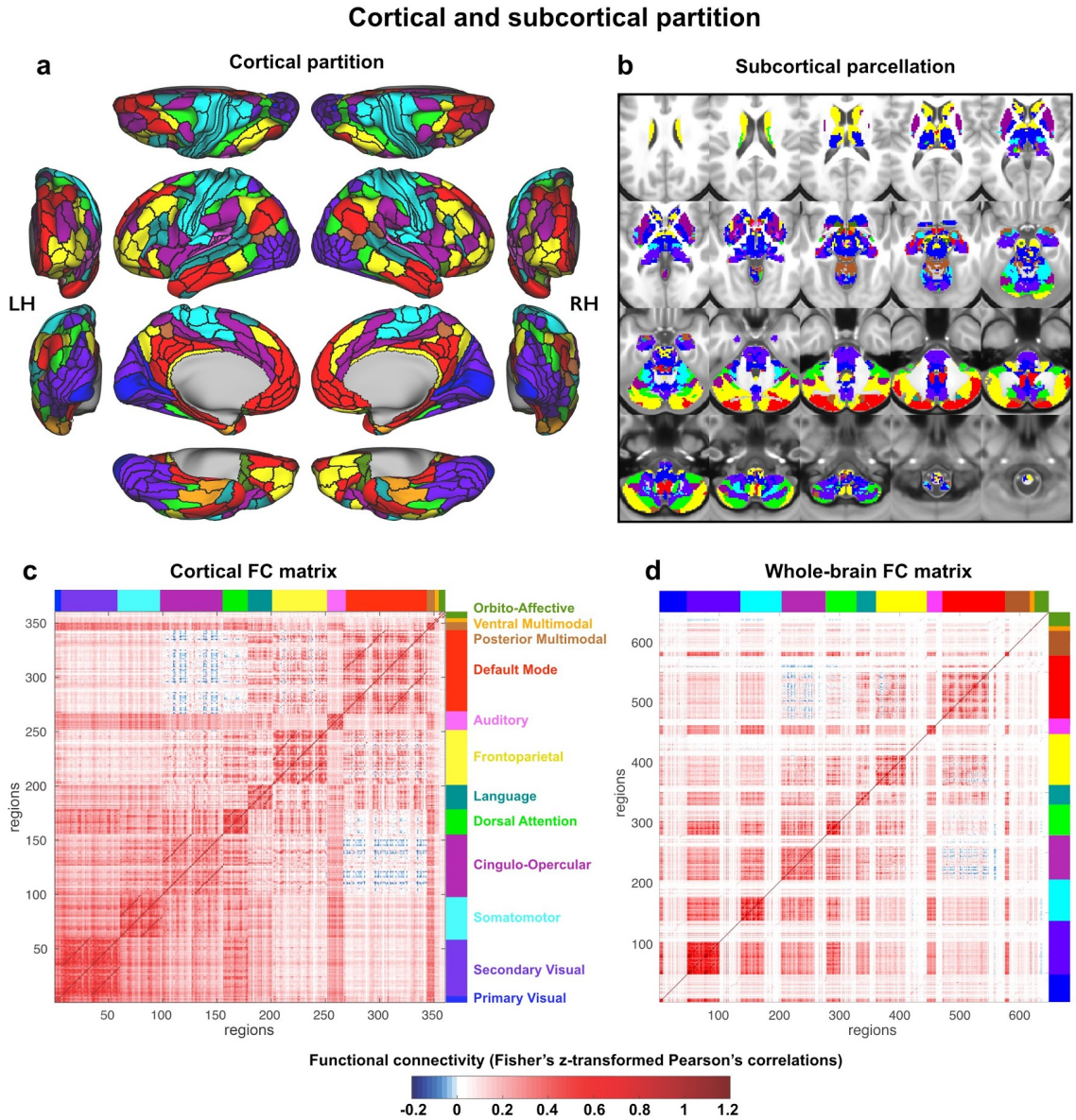


Figure 1. Cortical-subcortical network partition. A) The cortical network partition, as calculated with cortical surface resting-state fMRI data using graph community detection. We focused on identifying the network level of organization based on interactions among the next-lowest level of organization – functional regions. Network detection was calibrated based on identification of the well-established primary sensory-motor cortical systems (visual, somatomotor, auditory). Identifying clusters of functionally-defined cortical regions revealed many known and several unknown large-scale networks. **B**) The network partition identified in cortex was extended to all subcortical gray matter voxels. Briefly, each voxel was assigned to the cortical network with the strongest average resting-state functional connectivity (FC) with that voxel. **C**) The region-with-region FC matrix within cortex, sorted by network assignment. The block-like structure along the diagonal provides a visualization of the greater FC strength within (relative to between) each network. The darker off-diagonal lines reflect stronger cross-hemisphere FC within networks (since left hemisphere regions are listed first within each network). **D**) The parcel-to-parcel FC matrix, including both cortical and subcortical parcels. Note that the tendency for FC values in

subcortical parcels to be lower relative to cortical parcels was expected due to the use of multiband MRI with a 32-channel coil during data collection (see **Methods**).

Briefly, we used graph community detection to identify clusters of highly interconnected cortical regions based on RSFC (**Fig. 2A**; see **Methods** for details). We used a standard community detection algorithm that identifies communities by optimizing for modularity (high within-network and low between-network connectivity strength) (Blondel et al., 2008). Several principles were used to calibrate the definition of network communities as we searched over different "resolution" (gamma) parameters in the community detection algorithm: i) We required that primary sensory-motor cortical regions (visual, auditory, somatomotor)—which have been known for over a century to be functionally distinct neural systems (Fritsch and Hitzig, 1870)—would be identified as separate functional networks. Such separation was clear at the default "resolution" setting of the community detection algorithm (gamma=1) for separation of visual and somatomotor networks, but the auditory network was merged with the somatomotor network. We therefore increased the community resolution parameter until auditory and somatomotor networks separated. ii) We optimized for stability (similarity of network partitions across neighboring parameter settings) and iii) we optimized for modularity (high within-network and low between-network connectivity strength) (**Fig. 2B**). This approach revealed 12 networks consisting of well-known sensory-motor networks, previously-identified cognitive networks, and novel networks.

Well-known networks included primary visual (VIS1), secondary visual (VIS2), auditory (AUD), and somatomotor (SMN) networks. Previously-identified cognitive networks—networks identified in the last few decades—included the cingulo-opercular (CON), default-mode (DMN), dorsal attention (DAN), and frontoparietal cognitive control (FPN) networks. Two primary functional network atlases were used to identify these previously-identified networks: Power et al. (2011) (which was updated by (Cole et al., 2013)) and Yeo et al. (2011). Novel networks included the posterior multimodal (PMM), ventral multimodal (VMM), and orbito-affective (ORA) networks. We include additional analyses below to better establish the robustness of these networks, given that they have not (to our knowledge) been previously described. Notably, we also identified a language network (LAN), which has been known for over a century (Broca, 1861; Wernicke, 1874), yet has been missing from most previous atlases of large-scale functional networks (Power et al., 2011; Yeo et al., 2011). We include additional analyses below to establish that this network is involved in language functions and is likely equivalent to the previously-characterized left-lateralized language network consisting of Broca's area and Wernicke's area (among other language-related regions).

Figure 2

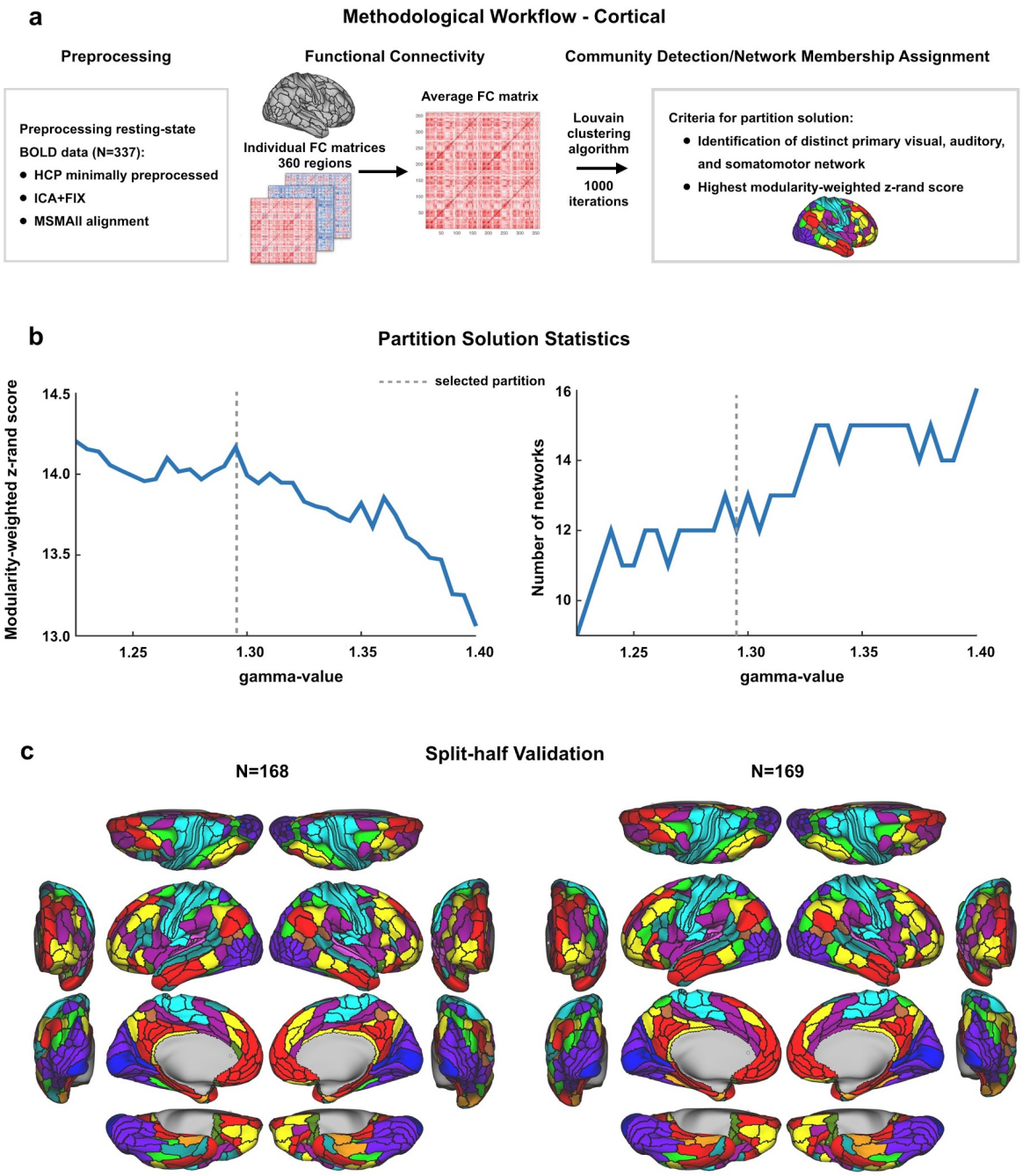


Figure 2. Cortical partition solution workflow and statistics. A) Schematic workflow used to create cortical partition. Data were preprocessed for 337 subjects, functional connectivity was calculated between all regions for each subject, and an FC matrix was constructed for each participant. After averaging across subjects, the Louvain clustering algorithm was run with 1000 iterations to detect communities of networks for a range of gamma-values. The final cortical partition was a result of two criteria; a plausible number of networks that included primary sensory/motor networks had to be present, and the most stable and maximally modular partition solution was chosen. **B)** Plots presenting the modularity-weighted z-rand

scores and number of networks in the partition for each gamma-value. The dashed line indicates at which gamma-value the community detection gave the most stable and (neurobiologically) plausible results. **C)** Split-half validation results for the cortical partition. The original dataset was split in two smaller sets consisting of matched subjects' data and the Louvain clustering algorithm was run with the same parameters as for the original partition. The two resulting network partitions were both highly similar to the original one presented in Fig.1A, indicating that our partition is reliable. See main text for more details.

Subcortical Extension of the Cortical Network Partition

Previous functional atlases of the human brain have focused primarily on cortical network assignments. However, it is well established that vital neural computations are also implemented by subcortical regions. Furthermore, many of the subcortical nuclei form functional loops, via the thalamus, with cortical territories. Thus, we expanded our network mapping across subcortical structures in order to develop a comprehensive whole-brain functional network atlas. We built on recent efforts to extend cortical network definitions into cerebellum (Buckner et al., 2011) and striatum (Choi et al., 2012), but extended our network assignment to all subcortical structures, additionally including: thalamus, hypothalamus, amygdala, hippocampus, brainstem, and all of basal ganglia, in addition to all other subcortical nuclei.

Briefly, we assigned each voxel to the network with which it shared the highest mean connectivity (defined as Pearson's correlation) across cortical parcels. We then implemented a number of quality control cleanup steps to eliminate small parcels that may be noise-driven, or that may have been driven by partial volume effects near the cerebellum (**Fig. 3A**; see **Methods** for details). Parcels were also constrained to anatomical boundaries between major subcortical structures, as defined by Freesurfer, to conform to the gross anatomy of the subcortex. Put differently, a subcortical functional network parcel in the striatum would not 'bleed' over into the thalamus unless it was independently defined as such explicitly within the thalamus. This resulted in a largely symmetric solution with 288 subcortical parcels (**Fig. 1B**) that was highly replicable across split-half samples, both qualitatively (**Fig. 3B-C**) and quantitatively (**Fig. 3D-E,** see **Methods**). The proportion of voxels that were assigned to the same network in both Discovery (N=168) and Replication (N=169) samples was highly significant above chance expectations for all networks (**Fig. 3D**). After quality control cleanup steps were performed for each of these split-half solutions, the proportion of replicated voxels increased for all networks (with the exception of LAN and VMM, **Fig. 3E**). Critically, we found that all 12 cortical networks, including higher-order associative networks (such as the FPN and CON), were represented in the subcortex with predominantly symmetrical and robustly replicable representations.

In addition, we computed a subcortical network assignment using resting-state data with GSR, due to concerns that low SNR in the subcortex may have led to extensive assignment of voxels to the visual networks (see **Methods**). This parcellation is presented in **Supplemental Figure S4** and is also available as part of our public release. Voxelwise network assignment and cleanup steps were performed identically to the original version without GSR, as described above. The subcortical parcellation using GSR data produced 358 distinct parcels after all cleanup steps, and showed less extensive representation of the visual networks, as predicted. 36.30% of voxels in VIS1 and 33.18% of voxels in VIS2 from the original parcellation were stably reassigned to the same network in the GSR parcellation (**Supplemental Figure S4c**). However, the number of voxels with stable assignments was significantly above chance for all networks given the total number of voxels in the subcortex, and for five of the networks (SMN,

CON, LAN, FPN and DMN) over 90% of the voxels were stably reassigned in the GSR parcellation.

Figure 3

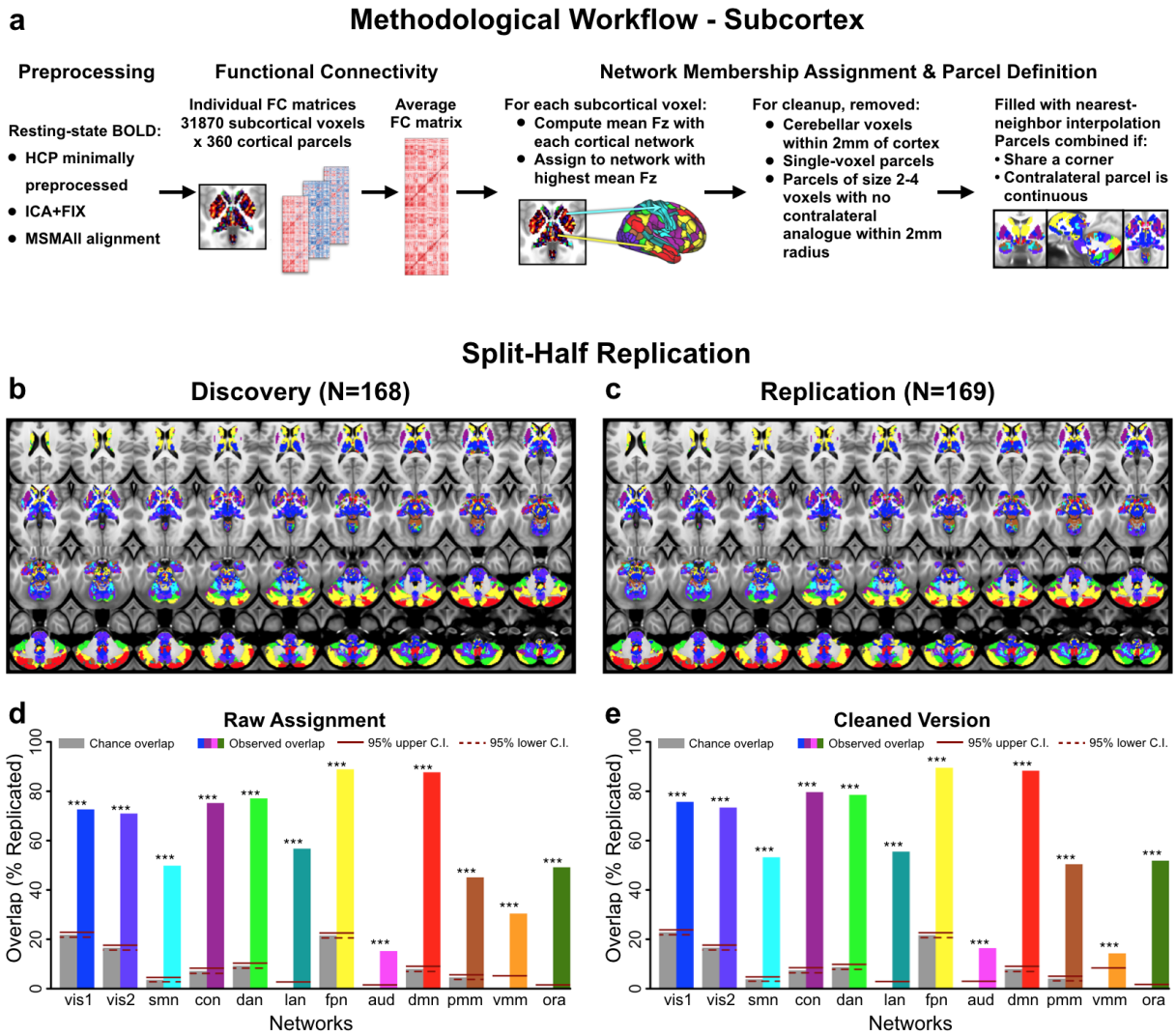


Figure 3. Subcortical partition solution workflow and statistics. A) Schematic workflow used to create subcortical partition. **B & C)** Split-half replication of the subcortical partition. The subcortical network assignment procedure was performed independently on two smaller sets of subjects matched for demographic variables. **D)** Proportion of voxels in each network with replicated assignments, before any cleanup steps. Gray bars show proportion of voxels expected to replicate by chance given the size of each network. Solid and dashed red lines indicate upper and lower 95% confidence interval for chance, respectively. **E)** Proportion of voxels in each network with replicated assignments, after cleanup steps were performed (see **Methods**). The proportion of voxels with identical network assignments in both Discovery and Replication samples was significantly above chance for all 12 networks (p<0.05), suggesting that the subcortical solution is highly replicable.

Assessing Quality of Cortical-Subcortical Network Partition

We used a split-half analysis to estimate the reliability of the cortical network partition

(**Fig. 2C**). The identical algorithm (with identical parameters) was applied to a pseudo-random set of 168 subjects (selected from the total set of 337 subjects), and then independently to the remaining 169 subjects. The split-half sets were matched on a variety of demographics in order to reduce the chance that observed differences were driven by group differences of potential interest (e.g. age or gender). The 168 subjects were selected by first creating a random list of subjects then exchanging subjects between the groups such the 168 subjects were matched, at the group level, with the remaining 169 subjects on the following demographics: age, gender, handedness, and education. This analysis revealed a highly similar network partition across the the two independent matched samples (**Fig. 2C**): adjusted z-rand (Traud et al., 2011) of z=190.2 (p<0.00001) and 92.5% of regions with identical network assignments. These results demonstrate high reliability of the main cortical network partition.

To further quantitatively evaluate the cortical partition, we calculated a network assignment confidence score (**Fig. 4A&C**), inter-subject connectivity variability (**Fig. 4B&D**), and network RSFC pattern asymmetry (**Fig. 4E & Fig. 5D**) for each parcel and network. As shown in **Fig. 4A&C**, most networks exhibited broadly similar confidence, with a mean score of 0.36 (SD=0.08), indicating higher RSFC pattern correlation between a region and its assigned network than with other networks. Only ORA had a substantially lower confidence score (mean=0.19, SD=0.1), possibly as a result of lower SNR in regions assigned to the ORA network (mean SNR=152 with range 143-194) compared to other networks (mean SNR all networks=228, range 79-371).

We hypothesized that low confidence could reflect three potential sources: low SNR, high intersubject variability, or high participation (due to variably connected hubs that do not fit neatly into a single network partition). We evaluated these possibilities, as shown in **Fig. 4F**. SNR and confidence scores were not significantly correlated (r=0.06, p=.29), which is not consistent with the possibility that low SNR affected confidence score substantially in these data. Regions with higher participation coefficients, a measure indicating how distributed a node's edges are across networks (potentially violating the assumption of a modular network organization), exhibited lower confidence scores (r=-0.25, p<0.00001). This suggests that low confidence might be explained by connector hubs (connecting to multiple networks), but only partially. Low participation coefficients can also potentially result from low SNR (SNR-participation r=0.6, p<0.000001). Again, however, it is not likely that low SNR was a significant factor in our confidence score results, since participation and confidence were still similarly negatively correlated when SNR was regressed out (r=-0.34, p<0.00001). Note that participation coefficient was calculated on the single-subject level, ruling out the possibility that high inter-subject variability drove the participation results.

Together, these results suggest network assignment quality was primarily influenced by high participation coefficient (strong RSFC with multiple networks) rather than low SNR. This suggests that the human brain violates modularity to some extent, reducing assignment confidence because some regions are connected to multiple networks. Note, however, that connectivity of single regions with multiple networks is not entirely surprising since the brain must somehow integrate functionality between networks, which requires variable inter-network connectivity. These results suggest the degree of multi-network connectivity may be small overall, however, since participation accounts for only 6.25% of the linear variance in confidence scores (participation-confidence r=-0.25; $r^{2=}$0.0625).

We also expected that low confidence could be driven by high inter-subject connectivity variability, which we calculated as the mean dissimilarity of a given region's cortex-wide RSFC

pattern across subject. This could have been driven by the kinds of subject-to-subject variability in RSFC patterns shown in several recent studies (Braga and Buckner, 2017; Gordon et al., 2017). Inconsistent with this being a major factor, we found a relatively homogeneous level of inter-subject variability across the Glasser parcels (**Fig. 4B**), with a mean variability score of 0.42 (SD=0.13) for the networks (**Fig. 4D**). Overall, most networks exhibited low inter-subject connectivity variability, relative to a maximum value of 1.0 (in which every subject's connectivity pattern would differ completely from every other). One network with higher inter-subject variability was the VMM network (mean=0.59, SD of 4 VMM regions=0.006), but this network's high confidence score suggests its networks assignment are nonetheless accurate overall. The ORA network also showed numerically higher inter-subject connectivity variability between subjects compared to the other networks (mean=0.7, SD of 6 ORA regions=0.15), in concordance with this network's lower confidence score. Note that rather than true inter-subject variability this may have been driven by somewhat lower SNR (i.e., greater measurement noise) in ORA regions (Spearman correlation between ORA inter-subject variability and SNR: r=-0.25, $p<0.00001$), likely due to MRI signal dropout from nearby sinuses. These results suggest some details are lost by using group-level RSFC (rather than individual-level RSFC) to identify networks, but that most network assignments are likely accurate and highly replicable.

We additionally assessed partition quality by quantifying inter-hemispheric asymmetry, under the assumption that most networks would be highly symmetric across the hemispheres. This metric served as a 'proxy' test of reliability, since we did not constrain the network partition to be symmetric. Asymmetry scores were calculated as the dissimilarity of cortex-wide RSFC patterns across hemispheric homologues (see **Methods**). Asymmetry results in **Fig. 4E** show that for most regions/networks RSFC patterns were very similar to a region's/network's homologue on the contralateral hemisphere (network mean=0.05, SD=0.04; all far below complete asymmetry of 1.0). As an exception to this, which was expected based on the language neuroscience literature, was the LAN network having the highest cortical asymmetry score. This reflects the left lateralization of this network (see also **Fig. 5** and additional analyses for LAN below), with 14 LAN regions on the left hemisphere vs. 9 regions assigned to LAN by the Louvain algorithm on the right hemisphere. Overall, this result further demonstrates the quality of the network partition, given that all expected network showed substantial inter-hemispheric symmetry with the sole exception of the LAN network.

Figure 4

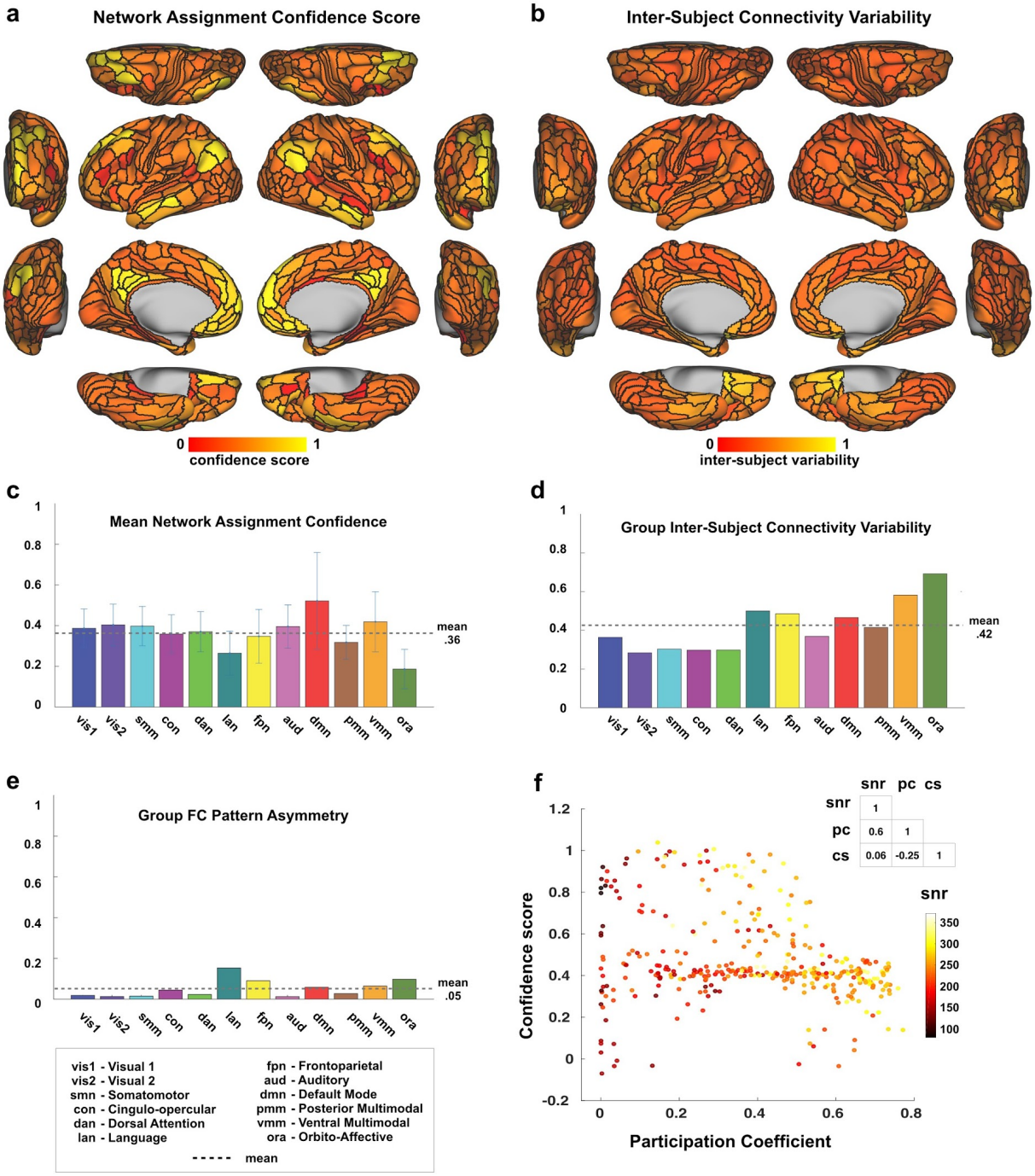


Figure 4. Quantitative assessment of cortical network partition. A) Cortical map with Network Assignment Confidence scores, reflecting a region's fc pattern similarity (calculated using Spearman's rank correlation) to its assigned network divided by similarity to all other networks. These scores are used as a

measure of certainty that the network to which a parcel was assigned is the correct one. The relatively homogeneous map indicates similar confidence across regions. **B)** Cortical map displaying Inter-Subject Connectivity Variability, a measure comparing the connectivity patterns for each region across subjects. Similar to panel A, most cortical regions appear to have highly similar values. **C)** Network averages of the parcel-level network assignment confidence scores (in panel A) are displayed. Error bars indicate standard deviations. Highest confidence scores were found in DMN and lowest in the new orbito-affective network (but note the lower SNR in this area). **D)** Group Inter-subject connectivity variability scores averaged across networks. See **Results** and **Methods** for details. **E)** Group FC Pattern Asymmetry, reflecting similarity between a region's (unilateral) functional connectivity pattern and that of its supposed homologue region on the opposite hemisphere. Note the relatively high asymmetry for the language network (LAN) resulting from the left-lateralized language parcels in our partition. **F)** Scatterplot showing the relationship between Network Assignment Confidence score, Participation Coefficient and SNR for each parcel. The table contains Pearson correlation values between the three measures. The non-significant correlation between Confidence and SNR indicates that Confidence scores were not substantially affected by SNR. However, a negative correlation between Confidence and Participation Coefficient could indicate that lower confidence regions partly consist of connector hubs that are shared between multiple networks.

Characterizing the Laterality and Function of the Language Network

As mentioned above, the network identified as a language network (LAN, including well-known language-related areas such as Broca's and Wernicke's areas) showed high asymmetry for its regions' cortex-wide RSFC patterns. To further test the hypothesis that this network carries out language-related functionality, we first analyzed the LANGUAGE task fMRI data provided by the HCP to map the amount of overlap of the derived whole-brain LAN network with language-activated grayordinates (see **Fig. 5A&B** for cortical and subcortical maps). This overlap was significantly higher than expected by chance (**Fig. 5C**), suggesting that these areas are indeed largely overlapping with language processing areas (>85% observed overlap). Second, we quantified the network's asymmetry (see **Methods**) by calculating asymmetry for each cortical parcel (**Fig. 5D**) and subcortical voxel (**Fig. 5E&F**). Compared to other networks, the LAN network was appreciably more asymmetric in cortex (LAN vs VMM: $t(336)=3.38$, $p=0.0008$, LAN vs. mean of all other networks: $p<0.00001$, also see **Fig. 4E**). Further, there were more LAN parcels identified in the left hemisphere (14 parcels) than the right hemisphere (9 parcels) of cortex. Also in subcortex, LAN emerged as one of the most asymmetric networks, as can be seen when comparing the proportion of non-overlapping subcortical voxels in left and right hemispheres. Similar left lateralization as in cortex was observed in subcortex when quantifying the proportion of total voxels in left and right hemisphere (left and right reversed for cerebellum, as expected). This asymmetry far exceeded chance levels (chance proportion of voxels in left subcortex/right cerebellum for all networks=0.50; proportion of voxels in left subcortex/right cerebellum for LAN=0.71;$\chi^2=8.878$, $p=0.0029$). In turn, we focused on a single asymmetric left-lateralized LAN region, area PSL. RSFC seed maps of left and right PSL (**Fig. 5G&H**) were strikingly different, with left PSL showing high LAN connectivity and low CON connectivity, but right PSL showing the opposite pattern. The LAN regions overlapping with language task activations, observed strong left-lateralized lateralization, and qualitatively-distinct connectivity patterns in asymmetric regions together strongly support the hypothesis that this network implements language functionality.

Figure 5

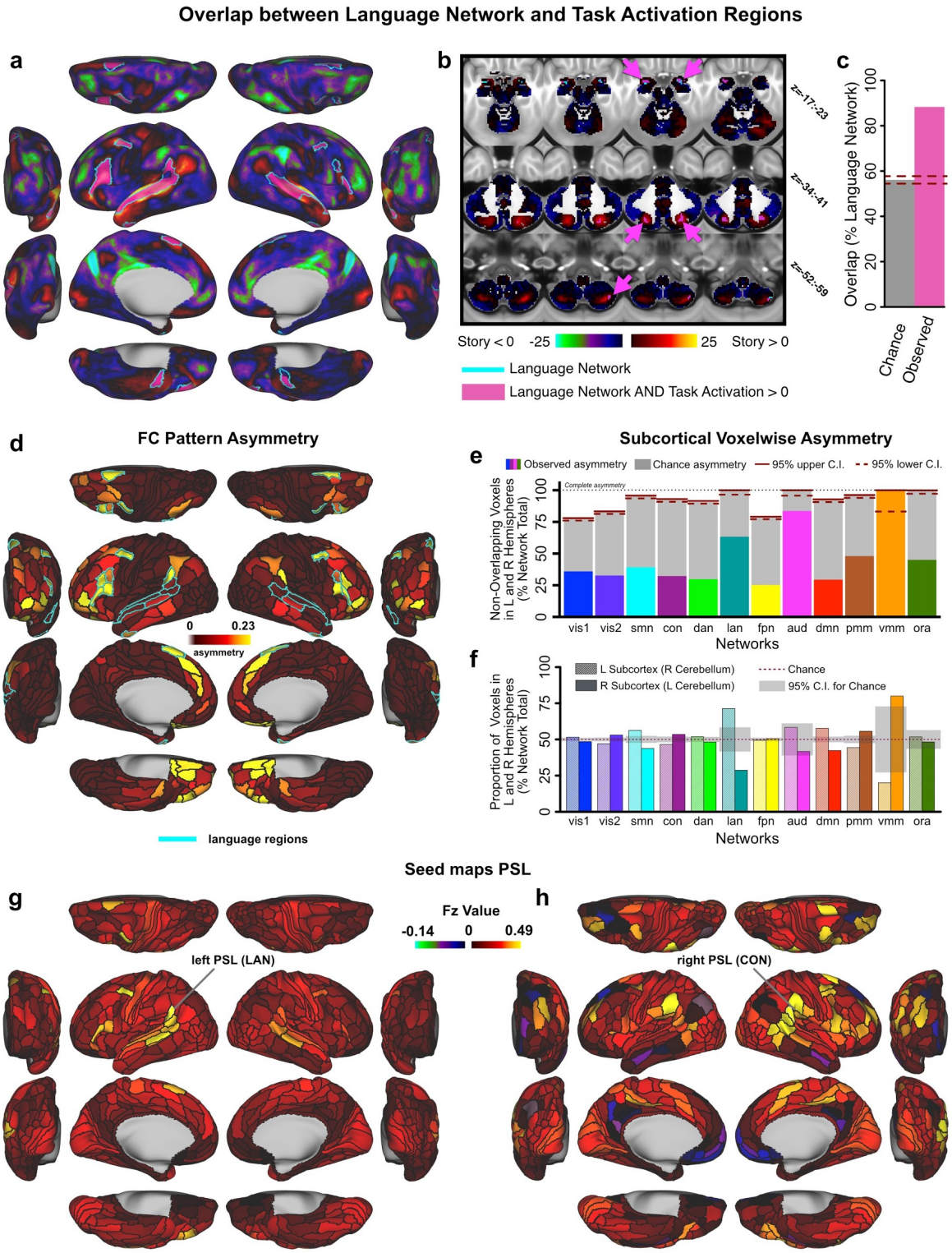


Figure 5. Language network evaluation. A & B) Overlap between the language network (LAN, teal outline) from our resting-state based network partition and activations from an independent language processing task (collected in the same sample of 337 subjects) in cortical and subcortical regions. Pink

areas indicate overlap between LAN and task activation. Underlay shows task activation t-statistics from the 'Story versus Baseline' contrast of the LANGUAGE task, replicating the analysis conducted by Glasser and colleagues (2016). Note that t-scores are shown here because the high statistics resulted in infinity values when converting to Z-scores. **C)** Percentage overlap between LAN and task activation in the language processing task expected by chance (gray bar) and actual observed overlap in panels A&B (pink bar). Dashed lines indicate 95% confidence intervals. **D)** Cortical map displaying the asymmetry of parcels. The teal outline indicates the language network, which is highly asymmetric compared to the other networks, with left hemisphere dominance. **E&F)** Network asymmetry in the subcortex. Colored bars in Panel E show the proportion of subcortical voxels in each network that do not overlap when comparing left and right hemispheres. Complete asymmetry (no overlap) is indicated by dotted line at 100% for reference. gray bars indicate chance asymmetry calculated given the size of each network. Solid and dashed red lines indicate 95% upper and lower confidence intervals for chance respectively. Panel F displays the proportion of total voxels in left and right hemispheres for each network. Chance level for this measure is 50% for all networks; confidence intervals are calculated given the total number of voxels in each network. Because functional representation of left and right is reversed in the cerebellum relative to the rest of the brain (due to the midline crossing of projecting fibers (van Baarsen et al., 2016)), left and right cerebellar hemispheres were exchanged in calculating this measure. Like the cortical networks, panel E&F show that subcortical networks are symmetric in general, with a left lateralized LAN. In subcortex, VMM is also significantly asymmetric. **G&H)** Functional connectivity seed maps for left and right perisylvian language areas (PSL) based on resting-state data in 337 subjects. Both the left and right language seed area show strongest connections to ipsilateral regions.

Identification of Novel Functional Networks: Posterior Multimodal, Ventral Multimodal, and Orbito-Affective Networks

Three networks emerged from the reported network detection approach that, to our knowledge, do not correspond to previously-described large-scale networks in the human brain (**Fig. 6**). These networks include PMM (posterior multimodal), VMM (ventral multimodal), and ORA (orbito-affective) networks. We found converging evidence to support the robustness of all three networks. First, all three networks were present for both groups of subjects in the cortical split-half analysis (**Fig. 2C**). Second, all three networks had subcortical voxels assigned to them (**Fig. 3 and Fig. 6**), with statistically significant (above chance, $p<0.05$; see **Methods**) split-half replication of those assignments (**Fig. 3D & E**). Third, the PMM and VMM networks were within one standard deviation of the cross-network mean confidence scores (**Fig. 4D**), suggesting equivalent confidence in these networks as better-established networks. While the ORA network exhibited the lowest confidence score, it was still well above chance, consistent with ORA regions having higher RSFC among themselves than with regions of other networks. Fourth, the inter-subject variability across the PMM network RSFC patterns was near the mean value across all networks (PMM inter-subject variability=0.41, cross-network mean=0.42), suggesting that PPM inter-subject variability was not appreciably different. In contrast, the VMM and ORA networks had somewhat higher inter-subject variability than the cross-network mean. While it is not possible to assess statistical significance of this result (due to this statistic being calculated across all subjects simultaneously, precluding the ability to use, e.g., t-tests), the high symmetry and replicability of these networks suggest these networks are well-defined. Together these results suggest that the three novel network identified here are robust and are therefore likely to be of broad functional relevance. It will nonetheless be important for future studies to further validate the existence of these network and better determine their functional roles.

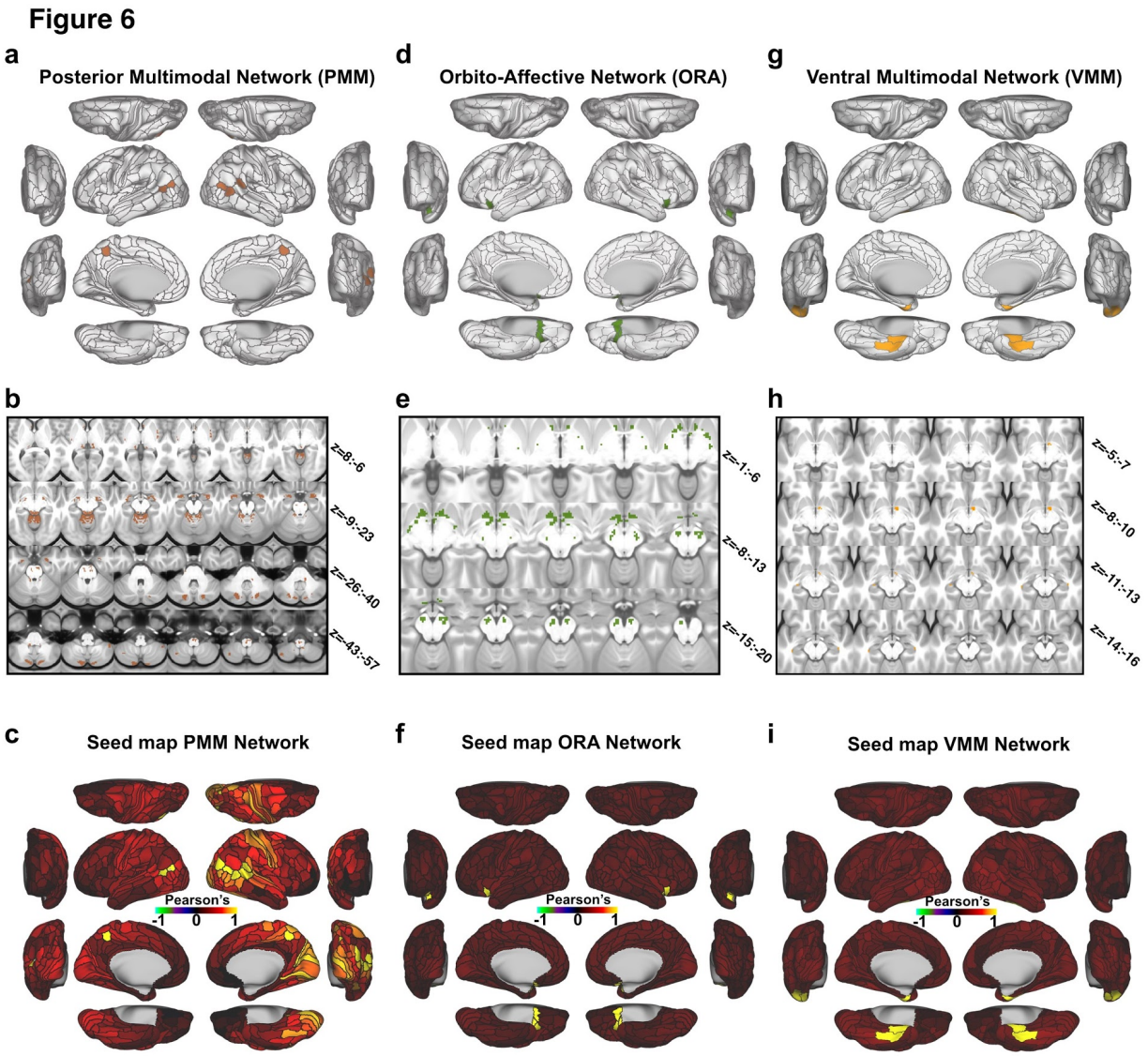


Figure 6. New posterior multimodal, orbito-affective, and ventral multimodal networks. A) Cortical parcels that are part of the posterior multimodal (PMM) network as detected by the Louvain clustering algorithm. **B)** Subcortical areas that were identified as PMM based on correlation with cortical regions. **C)** Cortical seed map of the PMM network showing connectivity to all other parcels (within-network connectivity is 1 in all PMM parcels). **D)** Cortical parcels that make up the orbito-affective (ORA) network as detected by the Louvain clustering algorithm. **E)** Subcortical areas associated with the ORA network. **F)** Cortical seed map of the ORA network showing connectivity of this network to all other cortical parcels. **G)** Cortical parcels that are part of the ventral multimodal (VMM) network as detected by the Louvain clustering algorithm. **H)** Subcortical areas associated with the VMM network. **I)** Cortical seed map showing connectivity of the VMM network to all other parcels.

Improved Reproducibility and Statistics of Language-Related Activation Using the Cortical-Subcortical Network Partition

We next sought to demonstrate the practical utility of the network partition and its beneficial impact on actual data analysis. The partition could be applied in a variety of ways,

such as interpreting task-evoked activations or functional connections in terms of a canonical set of functional networks. For this demonstration we focused on the identification of a putative "language" network. If this mapping is veridical in relation to the language system, then we hypothesized two effects to emerge: i) There should be high overlap between the language network and the task-evoked signal produced by the 'Story versus Baseline' LANGUAGE task (demonstrated in **Fig. 5**); ii) There should be an appreciable statistical improvement in the 'Story versus Baseline' LANGUAGE task contrast when going from a 'dense' grayordinate-level effect to a parcellated effect (as shown for several language-related local areas by Glasser et al. (2016)) in language network regions. Additionally, if the identified language network indeed maps onto independently-defined language-related task-evoked fMRI signal, then there should be even greater statistical improvement if computing the GLM-derived task-evoked signal across the entire language network. Showing such a statistical improvement would demonstrate a powerful and empirically useful application of the network partition for detecting neurocognitive effects in a more robust way.

To address the second hypothesis, we calculated statistics for the 'Story versus Baseline' LANGUAGE task contrast after separately fitting the task GLM to: dense grayordinate-level time series data (**Fig. 7A-B**, identical to underlay in **Fig. 5A**), time series data averaged within a given parcel (**Fig. 7C-D**), and time series data averaged within a given whole-brain network (**Fig. 7E-F**). As hypothesized, the t-statistic across the whole-brain LAN network was markedly higher when data were first averaged at the network level before fitting the task GLM, compared to fitting the task GLM on the 'dense' grayordinate level or parcel-level time series and then averaging across LAN regions (network t=24.71; parcel mean t=12.38, SD=10.91; dense mean t=8.50, SD=6.98; **Fig. 7G**). This effect was robustly present within the cortex (network t=24.71; parcel mean t=10.93, SE=11.66; dense mean t=8.74, SD=7.00; **Fig. 7H**) and the subcortex (network t=24.71; parcel mean t=1.45, SD=3.86; dense mean t=3.37, SD=3.72; **Fig. 7I**). Overall, t-statistics for all three LANGUAGE task contrasts were markedly improved by fitting the task GLM to parcel-level time series, rather than fitting to dense time series and averaging across parcels afterwards (**Fig. 7J**, note sigmoidal deviation from diagonal). Importantly, t-statistics were further improved when the task GLM was fit on network-averaged time series, compared to parcellating by network after fitting on dense (**Fig. 7K**) or parcel time series (**Fig. 7L**). This result strongly supports that the signal-to-noise ratio was substantially improved by first averaging BOLD time series data within the identified LAN network. Of note, this result also reinforces the inference that the LAN asymmetry reflects true lateralization. Together, these task-evoked effects add confidence to the identified language network definition and demonstrate the practical utility of the network partition, which is released publicly as part of this study.

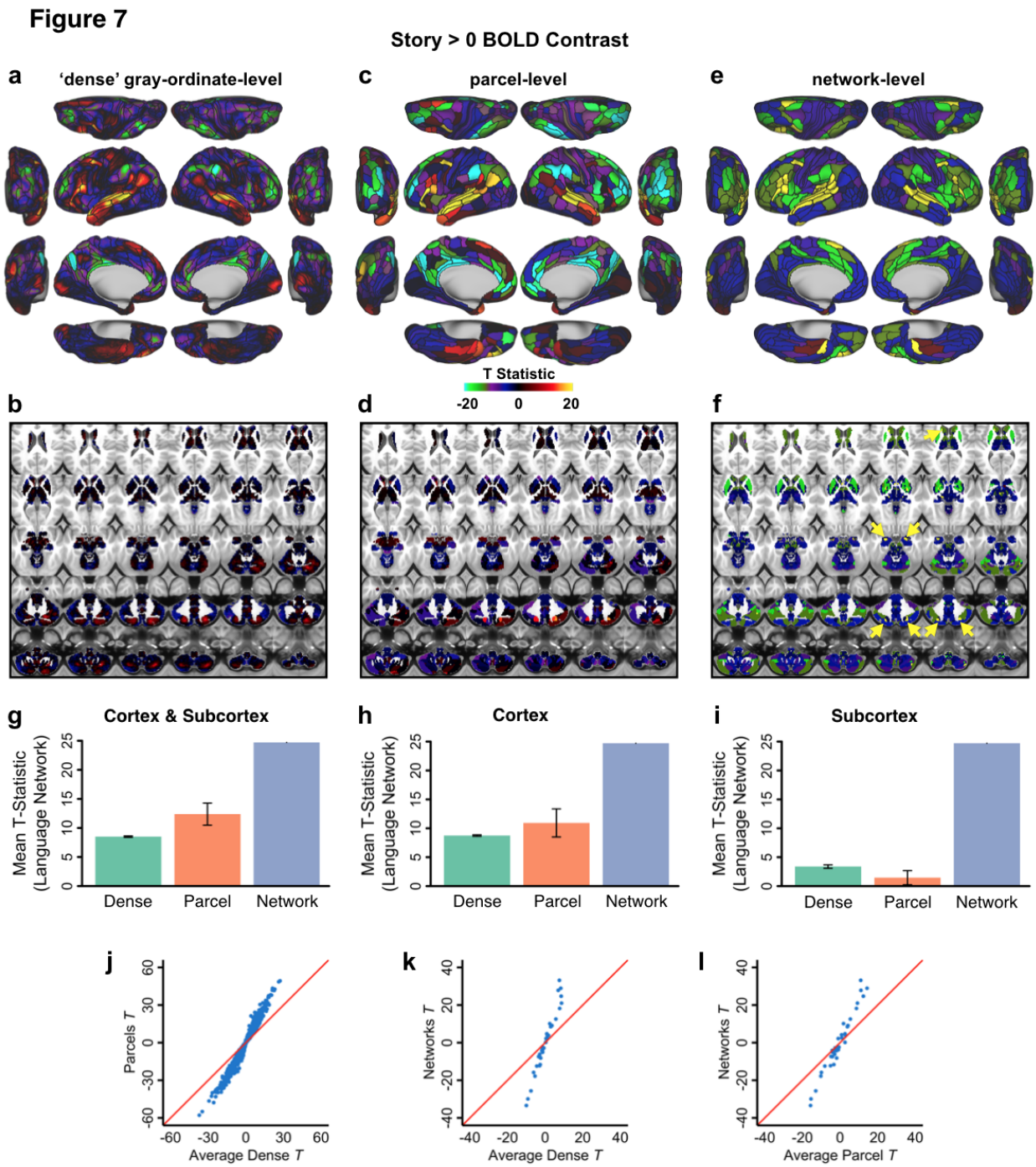


Figure 7. Demonstration of improved reproducibility and statistics with new partition. Panels A-F show task activations for a language processing (LANGUAGE task 'Story versus Baseline' contrast) task at three different levels. **A)** Cortical activation map of dense-level analysis. **B)** Subcortical activation map of dense-level analysis. **C)** Cortical activation map of parcel-level analysis. Task fMRI data were first parcellated at the parcel level before model fitting. **D)** Subcortical activation map of parcel-level analysis. **E)** Cortical activation map of network-level analysis. Task fMRI data were first parcellated at the network level before model fitting. **F)** Subcortical activation map of network-level analysis. Yellow arrows highlight subcortical regions with a high task-activated t-score, which overlap with parcels in the LAN network. **G)** t-statistics (LANGUAGE task 'Story versus Baseline' contrast) shown in panels A-F significantly improve for the parcel-level vs. dense-level analysis, and for the network-level vs. parcel-level

analysis in a combined cortex and subcortex analysis. Error bars are inter-parcel standard deviations. **H)** t-statistics (LANGUAGE task 'Story versus Baseline' contrast) in cortex alone again show significantly better results for the network-level analysis compared to the dense- and parcel-level analyses. **I)** t-statistics (LANGUAGE task 'Story versus Baseline' contrast) in subcortex showed substantially better results for the network-level analysis compared to the dense- and parcel-level analyses. Note that—in contrast to the results for cortex—parcel-level analysis in subcortex does not give an advantage over dense-level analysis. **J)** An improvement in t-statistics was found when task designs were fit on parcellated time series instead of on dense time series and subsequently averaging for parcels. Blue dots represent 648 parcels × 3 LANGUAGE task contrasts ('Story versus Baseline'; 'Math versus Baseline'; 'Story versus Math'). **K)** Improvement in t-statistics was also found when fitting task designs on network time series compared to fitting on dense time series and then averaging for networks. Blue dots represent 12 networks × 3 LANGUAGE task contrasts. **L)** A further improvement in t-statistics was found when fitting on networks versus fitting on parcels and then averaging for networks. Blue dots represent 12 networks × 3 LANGUAGE task contrasts.

DISCUSSION

The human brain is a unified dynamical computational system that, ultimately, can only be understood as a whole. Simultaneously, understanding any dynamical system requires identifying its functional components and their interactions. We therefore sought to create a whole-brain network partition, identifying large-scale network communities of brain regions across both cortex and, for the first time, all subcortical areas. This provides a novel network organization that, unlike previously-developed network partitions, includes all major portions of the human brain. We created this whole-brain partition as a resource to aid neuroscience research generally, and we are therefore releasing the partition (along with the data and code that produced it) to the neuroscience community (available at https://github.com/ColeLab/ColeAnticevicNetPartition once through peer review).

The human brain consists of multiple levels of functional organization. As with other natural organized dynamical systems, each level consists of sets of interacting elements. For instance, cellular subcomponents (e.g., ion channels) interact to form individual neurons, which then interact to form local circuits, which in turn interact to form brain regions. We focused on the next-highest level of organization: large-scale brain networks, each consisting of highly interactive communities of brain regions. This level of organization puts all other levels in a functional context. Thus, a single prefrontal neuron identified within what we label here as the FPN (frontoparietal cognitive control network) could be expected to interact with other FPN neurons, even if they are many centimeters away in parietal lobe. This has implications for interpreting the dynamics and functions of that single neuron. Thus, despite fMRI not having direct access to measurements of any single neuron's activity, the resulting large-scale functional network organization identified here using fMRI provides useful information for understanding all levels of brain organization. We hope the public availability of this brain-wide functional network partition will aid other researchers in identifying the mechanisms underlying brain functions across levels of organization.

As with all neuroscientific methods there are limitations to the approach used here (detailed below), but also several major advantages. First, we used a large dataset relative to most neuroscientific studies to date (337 subjects), increasing the effective SNR and the likelihood that the results will generalize to new groups of individuals. Second, we used multiple quality control metrics to ensure stability and reliability of the network partition, which proved to be extremely high by all applied standards. Third, we used a principled approach to decide on the

network partition algorithm and associated parameters, involving both stability optimization and calibration of parameters based on well-established neurobiologically-grounded constraints (e.g. the existence of primary sensory-motor networks). Fourth, we extended the cortical network partition to subcortical structures, resulting in a comprehensive map of brain-wide functional networks. Finally, we used task fMRI data to demonstrate a practical advantage of using this network partition: a substantial increase in the ability to detect network-level functional activations.

Notably, previously published large-scale network partitions have already made a substantial positive impact on neuroscientific investigations across health and disease. We expect the network partition developed here to be similarly impactful across a variety of neuroscientific investigations, improving scientific inferences relative to existing network atlases. For instance, the network partition could be used to interpret possible functions of a region-level activation using fMRI, EEG, or local field potentials. Alternatively, the network partition could be used in studies of network dynamics, placing interactions in a larger functional context to aid in summarizing and interpreting results. Another use of the network partition could be as a data reduction approach, increasing data processing efficiency while maintaining functionally-meaningful large-scale network units. Finally, this novel partition provides for the first time a possibility to test hypotheses about brain-wide functional network organization, spanning cortex, striatum, thalamus, amygdala, hippocampus, brainstem, the cerebellum, and other structures. It is also notable that unlike the brain region and brain network levels, lower levels of organization such as the neuron or local circuit are not expected to generalize across individuals. This is due to the very low likelihood of functionally-equivalent individual neurons aligning anatomically between individuals. Thus, like identifying brain regions, characterizing large-scale brain networks provides units of brain organization that can provide a testbed for the following question, "what does this brain structure do functionally across individuals?"—a key question for generalized understanding of human brain function.

Extending Prior Network Partitions to Converge on a Global Characterization of Human Brain Network Organization

The network partition identified here is, as expected, similar in many ways to previously-identified network partitions. However, there are several critical differences that provide novel discoveries regarding the large-scale network architecture of the human brain. Similar to both the Power et al. (2011) and Yeo et al. (2011) cortical network partitions, a variety of well-known sensory-motor and previously-discovered cognitive large-scale functional networks were identified. Common to both of these network partitions, we identified FPN, CON, DMN, DAN, visual, and somatomotor networks. Unlike Yeo et al. but similar to Power et al., we identified a separate auditory network consistent with the primary auditory cortical system. Notably, this auditory network was merged with the somatomotor network at various parameter settings of our network detection algorithm, consistent with the Yeo et al. result (which used a K-means clustering approach). This illustrates the difficulty of identifying the correct 'data-driven' metrics when using a clustering algorithm—auditory and somatomotor regions are known to perform highly distinct functions yet their RSFC patterns were difficult to separate without explicitly forcing this neurobiologically plausible separation.

We identified three networks that, to our knowledge, have not been previously identified: PMM (posterior multimodal), VMM (ventral multimodal), and ORA (orbito-affective). Unlike the language network, we did not predict the existence of these networks based on the prior

literature. Importantly, lack of pre-existing evidence of the VMM and ORA networks was likely driven by signal dropout in the proximity of these networks, due to magnetic field inhomogeneities from nearby sinuses (Deichmann et al., 2003). The multiband fMRI data used here (Uğurbil et al., 2013) appears to have reduced the signal dropout near sinuses. This is likely due to smaller voxels (2 mm cubic voxels used here rather than the standard-to-date 3+ mm voxels), which can reduce MRI signal dropout (Merboldt et al., 2000; Smith et al., 2013). The increased precision from using a cortical surface analysis (Anticevic et al., 2008), averaging across vertices within each parcel, and averaging with a large sample size likely all contributed to an increased ability to map RSFC in these dropout areas. While we found some evidence for lower SNR in these regions relative to other cortical regions, we also identified strong reliability of the networks using split-half validation and found a symmetric, replicable and robust subcortical contribution to these networks, further validating these networks. It will be important for future studies to corroborate the existence of these networks, identify their functional roles, and enumerate the factors (such as voxel size) that affect the ability to detect them.

It is unclear at this point what functions these networks might perform, given that they represent a novel discovery. While we appreciate this partially reflects reverse inference, we used observations of the constituent parts of the networks to infer possible functionality and provide a label. This is most evident in the case of the ORA network, which overlaps with portions of cortex associated with 'reward processing' functionality in posterior orbitofrontal cortex (Kahnt et al., 2011; Schultz, 2006). Corroborating this interpretation, ORA connected strongly with known reward-related areas in subcortex. These included the ventral striatum (Delgado et al., 2000; Schultz et al., 1992), midbrain nuclei consistent with the substantia nigra / ventral tegmental area (which contain dopamine neurons) (Fiorillo et al., 2003), and the globus pallidus (Justin Rossi et al., 2017). Further, this portion of cortex was modulated differentially by rewarding stimuli (Camara et al., 2010). This is consistent with a strong role for reward-related dopamine projections to ORA, suggesting strong reward processing functionality for this network.

The VMM network consists of four cortical regions on the ventral surface of the temporal lobe. The VMM extends into subcortex only minimally, with a cluster in the right ventral striatum and small bilateral clusters in the hippocampus. One possible function of this network is to represent higher-order semantic categories, consistent with studies of anterior (Rogers et al., 2006) and inferior temporal lobe (De Baene and Vogels, 2010). The novelty of this network reduces our ability to identify its functionality, however, such that it will be important for future studies to better determine what the functional specializations of this network might be.

The PMM network consists of bilateral dorsomedial parietal lobe, bilateral temporal-parietal-occipital junction, and right dorsocaudal temporal lobe. The PMM also extends into a variety of subcortical locations. These locations include: bilateral amygdala, portions of the brainstem, the putamen, multiple portions of cerebellum, a small portion of the caudate, a small portion of thalamus, and a portion of the diencephalon consistent with the basal forebrain. Most of these subcortical locations were assigned symmetrically across hemispheres and showed strong split-half replication. This demonstrates that while these assignments were widespread they were nonetheless robust, suggesting the existence of previously-unknown widespread PMM circuits. One possible function of this network could be spatial navigation, given the importance of dorsomedial parietal lobe for spatial navigation (Marchette et al., 2014). Additionally, PMM might be important for identifying and representing event structure in narratives, given that PMM regions were recently shown to represent long narrative structures during movie watching

(Baldassano et al., 2017). It will be important for future studies to carefully map the PMM as identified here to particular functions such as spatial navigation and representing situational/narrative structures.

Our ability to map the ventral surface of cortex presented a unique opportunity, since most previous network partitions omitted these territories due to MRI signal dropout. We not only identified two novel networks in these dropout zones, but were also able to test for expansion of previously-identified networks into an extensive portion of cortex for the first time. We found that orbitofrontal cortex (OFC) was split into thirds, with nearly equal assignment of OFC parcels to FPN, DMN, and ORA. It is notable that so much of OFC was assigned to FPN given that the FPN is classically described as primarily lateral prefrontal cortex and parietal cortex. This result suggests that the task-rule-oriented representations in lateral prefrontal cortex (Cole et al., 2011; Stokes et al., 2013) likely interact extensively with action-outcome and stimulus-reward associations in OFC (Kahnt et al., 2011). Indeed, some nonhuman primate studies have suggested such interactions occur during task performance (Wallis and Miller, 2003). The present study suggests these interactions occur as a part of a global system likely specialized for cognitive control and associated goal pursuit (Cole et al., 2013, 2014b; Duncan, 2010). It will be important for future studies to more fully characterize the relationships between classic portions of FPN and these portions of OFC previously unassigned due to MRI signal dropout.

Mapping a left-lateralized brain-wide language network in the human brain

Unlike both the Yeo et al. and Power et al. network partitions, we identified a network highly consistent with language functionality. This was based on the proximity of its regions to the well-established Broca's and Wernicke's areas, its left lateralization being consistent with known left lateralization of language functionality (Gazzaniga, 2005; Gazzaniga et al., 1962), as well as its activation during a language task. Additionally, several of the regions included in this network were thoroughly investigated by Glasser et al. (2016), establishing these regions as distinct functional entities with clear language functionality. Notably, the Power et al. (2011) partition (updated and visualized more fully by (Cole et al., 2013)) included a network consistent with this language network, but labeled the "ventral attention network". The present results suggest this network was previously mislabeled, since its connectivity pattern, anatomical location, and task activations are most consistent with language functionality.

One key feature of the language network identified here is its left lateralization. We found that the cortical language network was the most lateralized network in terms of RSFC pattern asymmetry (**Fig. 4E, 5G, & 5H**), that the subcortical voxels assigned to the language network were more left-lateralized than expected by chance (**Fig. 5E & 5F**), and that the language network overlapped more with language task activations than chance (**Fig. 5A, 5B & 5C**). Lateralization of language functionality is one of the most well-established findings in the human brain (Mesulam, 1998), making it somewhat surprising that this has not been emphasized in previous RSFC literature. A recent study (McAvoy et al., 2015) found that left-lateralized language functionality only emerged in their RSFC analysis when global signal regression was not included as a preprocessing step. Inconsistent with this, however, the Power et al. (2011) network similar to our identified language network was left lateralized (with dorsal and medial frontal network assignments being more extensive in the left hemisphere), despite use of global signal regression. Thus, while not performing global signal regression may have assisted our identification of the language network, it was unlikely that avoiding global signal regression was

necessary to identify this network.

Beyond simply counting more language-assigned parcels in the left hemisphere (14 left, 9 right), our use of pattern asymmetry was important for precisely quantifying lateralization. RSFC pattern asymmetry revealed that several language network regions had highly distinct global patterns of RSFC with their right-hemisphere homologues. This striking qualitative difference across homologous parcels is illustrated in detail in Figure 5G & 5H. This parcel, which is consistent with Wernicke's area on the left, was assigned with high confidence to the language network on the left but with high confidence to CON on the right. Consistent with this assignment difference, many regions with low RSFC for the left hemisphere parcel are high for the right hemisphere parcel, and vice versa. Together these results demonstrate the strength of left lateralization of the language network, both in terms of the number of left-lateralized parcels, asymmetry of global RSFC patterns, as well as its subcortical contributions.

Mapping the complex relationships between subcortical structures and cortical networks

We found that all 12 cortical functional networks, including higher-order associative networks (such as the FPN and CON), were reliably represented across the entire subcortex and the cerebellum. This is consistent with known functional loops between all portions of cortex and thalamus (Behrens et al., 2003), which in turn loop through basal ganglia (Middleton and Strick, 1994) and cerebellum (Kelly and Strick, 2003). Also consistent with the observed widespread connectivity between cortex and subcortical nuclei, various subcortical nuclei involving a variety of neurotransmitters (e.g., substantia nigra, basal forebrain, raphe nucleus) are known to project broadly throughout cortex (Herlenius and Lagercrantz, 2004). Finally, regions such as amygdala (Barbas, 2000; Jolkkonen and Pitkänen, 1998) and hippocampus (Eichenbaum et al., 2007) are thought to project to and from multiple cortical networks. Importantly, most of what is known about these subcortical structures comes from non-human animal studies or localized functional neuroimaging studies in humans, with relatively few focused RSFC studies (Buckner et al., 2011; Choi et al., 2012). The reported results represent the first comprehensive attempt to assign each subcortical voxel to a given cortical network. In turn, we establish the replicability, stability, symmetry and task-evoked relevance of such a subcortical functional network solution. Nevertheless, there were some unexpected findings that will be important to follow up on in future research. First, we found that the language network exhibits notable connectivity with the amygdala. Second, we identified a large and robust subcortical contribution to the primary visual network, perhaps reflecting a distributed 'attentional system', involved in overt attention and wakefulness. Of note, we did explicitly enforce a separate of the V1 and secondary visual cortical networks. Recent work suggests that there may be some residual artifact associated primarily with visual and somatomotor systems (respiration, sleep, movement) (Bijsterbosch et al., 2017; Glasser et al., 2017). It may be possible that assignment of some subcortical structures to VIS1 is inflated due to this artifact (perhaps due to eyes open vs. closed correlating with sleep+respiration changes). This current limitation that can be improved in future iterations of the partition by leveraging recently proposed advances in temporal de-noising that circumvents global signal removal (Glasser et al., 2017).

Importantly, prior subcortical network assignment attempts did not incorporate the thalamus and the brain stem in their reported solutions. As noted, thalamic sub-nuclei are well-known to form functional circuits with cortical networks (Barbas, 2000; Zhang et al., 2008) and have been shown to exhibit robust patterns of diffusion MRI-derived probabilistic tractography with cortical territories (Behrens et al., 2003). Therefore, it was vital to demonstrate that the

subcortical network solution captures the well-established thalamic nuclei configuration. A ubiquitously established thalamic structure is the lateral geniculate nucleus (LGN), which received initial visual inputs from the retina via the optic nerve and projects in an organized anatomical fashion onto V1 in the mammalian neocortex. Therefore, we established that our thalamic solution (irrespective of combining or separating the primary and secondary visual networks). We observed a well-preserved correspondence of the thalamic network assignment whereby the LGN was encompassed by the primary visual network (VIS1) or by the overall visual network (when combining VIS1 and VIS2 into a single visual system) (see **Supplemental Figure S3**).

Limitations and opportunities for further improvement of the network partition

There are several limitations to the approach used here that represent important opportunities for future improvements to understanding the large-scale functional organization of the human brain. For instance, any network partition necessarily oversimplifies brain organization by removing/downplaying inter-network interactions. Nonetheless, it is useful to know the overall network organization while acknowledging the smaller/rarer interactions between networks, which may be dynamic over time. Additionally, this is not a fully exhaustive search over all possible network organizations. Our partition was likely not fully optimal due to the need to use heuristics to identify network organization (for computational tractability) (Blondel et al., 2008; Girvan and Newman, 2002). This leaves open the possibility of more accurate network organizations in the future. Nonetheless, we assessed multiple algorithms and ran a large-scale parameter search, achieving a highly optimal and reliable network partition as quantified by a variety of quality assessment metrics.

Despite covering the whole brain (unlike most previous network partitions), we nonetheless maintained a cortical-centric approach. Specifically, we began by creating a cortical network partition, which was then extended into subcortical voxels by quantifying the relationship between subcortex with the cortical networks. This may introduce a cortico-centric bias as the subcortical solution is explicitly driven by defining the cortex partition first. Nonetheless, we used this approach to aid in bridging the currently cortico-centric view of human brain function to subcortical structures. We also used this approach given the historical utility of understanding subcortical functions based on connectivity with specific cortical structures. For instance, mapping cerebellar connectivity with cortex in macaque monkeys has aided in understanding functional specialization in cerebellum (Kelly and Strick, 2003). Furthermore, this approach has proved highly productive and impactful in prior attempts at mapping striatum and cerebellum onto cortical networks (Buckner et al., 2011; Choi et al., 2012). We nonetheless expect that future research will benefit from a more even-handed partitioning of cortical-subcortical gray matter. This would involve creating functional-defined three-dimensional brain parcels in subcortical structures, just as was done as an initial step in cortex (Glasser et al., 2016). These parcels would then be included in a community detection algorithm along with the cortical parcels. This may reveal distinct subcortical parcels from what we identified here, in addition to potentially distinct networks. Notably, it is possible that two functional parcels that are neighbors in anatomical space could be merged in our current approach if they were both assigned to the same network. Nonetheless, we expect that our approach has advanced understanding of subcortical structures, putting them in the functional context defined by large-scale cortical networks.

Additional improvements on the present network partition could stem from even more

precisely defining the cortical parcels. Presently used parcels were identified based on convergence across multiple neuroimaging modalities (e.g., fMRI and structural MRI), likely limiting biases from any one modality. Nevertheless, certain decisions were made when deriving this parcellation that may be reconsidered in future. For instance, the Glasser parcels force the face and non-face representations in the primary motor homunculus to be merged (since primary sensory and primary motor regions were defined in part based on cytoarchitecture), even though it is clear that these portions of the motor homunculus have distinct RSFC patterns (Power et al., 2011; Yeo et al., 2011). Despite such potential limitations the use of multiple modalities when defining parcels by Gasser and colleagues likely reduced biases present in any one modality (e.g., RSFC).

There is evidence that global signal removal (GSR) is important for reducing respiratory and motion artifacts that plague RSFC (Power et al., 2014, 2017). GSR was not used for the primary analyses of the current study because Glasser et al. (2016) reported that GSR appreciably shifts RSFC gradients (relative to other modalities only minimally affected by respiratory/motion artifacts) used for identifying the cortical parcels, which could invalidate use of these regions in the present study. However, we used GSR in a follow-up analysis to test the hypothesis that GSR could reduce the extensive assignment of low-SNR subcortical voxels to the visual networks (**Supplemental Figure S4**). As expected, the visual networks were less extensively represented in the version with GSR, but all networks were replicated significantly above chance and over 90% of the voxels were stable for five of the networks (SMN, CON, LAN, FPN and DMN).

Simultaneous with the present study an approach involving temporal independent components analysis (ICA) has been developed to remove global noise while leaving global signal of neural origin (Glasser et al., 2017). This results in RSFC with global noise distortions removed without GSR-driven distortions such as RSFC gradient shifts. Future work should generate a revised version of the partition after the parcellation has been re-computed using this new temporal ICA de-noising method.

Another opportunity for future improvement is to better characterize the hierarchical nature of brain network organization. This reflects the fact that network organization is likely hierarchical in the sense that each large-scale brain network could be broken down into smaller and smaller components, eventually reaching the single-region level. Critically, however, we used a principled approach to define our target level of organization by setting parameters to detect well-established primary sensory-motor cortical systems. Thus, we created a whole-brain network partition intentionally defined as being at (or near) the same level of organization as these well-established brain systems. We therefore expect that the calibration of our community detection algorithm likely identified networks in association cortex that are at the same (or a similar) level of organization, and are therefore of similar importance for higher-level cognitive functions as primary sensory-motor systems are for perceptual-motor functions.

Conclusions

The results presented here describe the current version (v1.0) of a novel whole-brain functional network characterization of the human brain. The primary purpose of this study is to describe the network partition dataset, which is now publicly available. We additionally reported a series of quality assessments and validations of the provided network partition. We found evidence that the partition was of high quality and exhibited robust replicability across independent samples as well as across cortical and subcortical structures. While we propose a

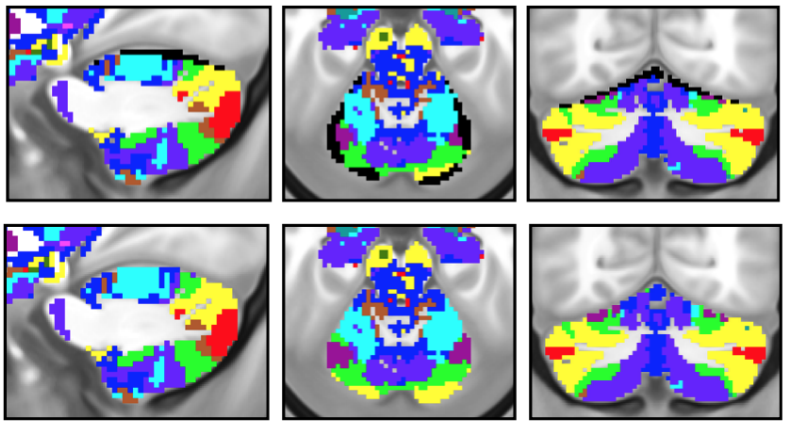
number of important future improvements of the provided version 1.0, this constitutes the most accurate estimate of whole-brain functional network organization in humans to date. We additionally demonstrated the existence of novel functional networks, such as the lateralized language network, providing additional understanding of human brain organization. The result was successfully applied to a language fMRI task, demonstrating strikingly improved statistical power to detect task-related activations when using the network partition. Collectively, this study demonstrates the value of this whole-brain network partition for scientific inquiry into human brain organization as well as specific task functionality.

Supplementary Material

Unassigned Cerebellar Voxels

a

b



c

	Voxel Count (Before Dilation)	Voxel Count (After Dilation)	% Increase
Visual	2017	2166	**7.39%**
Visual2	2613	2715	**3.90%**
Somatomotor	1107	1224	**10.57%**
Cingulo-Opercular	863	983	**13.90%**
Dorsal Attention	2745	2873	**4.66%**
Language	80	80	**0.00%**
Frontoparietal	4494	4604	**2.45%**
Auditory	0	0	**0.00%**
Default Mode	2223	2239	**0.72%**
Posterior Multimodal	927	969	**4.53%**
Unknown	0	0	**0.00%**
Orbito-Affective	0	0	**0.00%**
Unassigned	784	0	**-**
Total	**17853**	**17853**	

Supplemental Figure S1. Reassignment of cerebellar voxels near cortex. We removed cerebellar voxels within 2mm of the cortex from the initial network assignment to correct for any potential signal bleed-over from the adjacent cerebral cortex and/or partial volume effects. In the final step, nearby networks were dilated with nearest-neighbor interpolation to reassign these voxels. **A)** Subcortical network solution before dilation. Black indicates voxels removed from initial subcortical network assignment. **B)** Subcortical network solution after dilation. **C)** Table of voxel counts for each of the 12 networks in the cerebellum before and after the dilation step. The cingulo-opercular network exhibited the greatest percentage increase in size after dilation (13.90%, 120 voxels).

Subcortical Network Assignment Cleanup

a

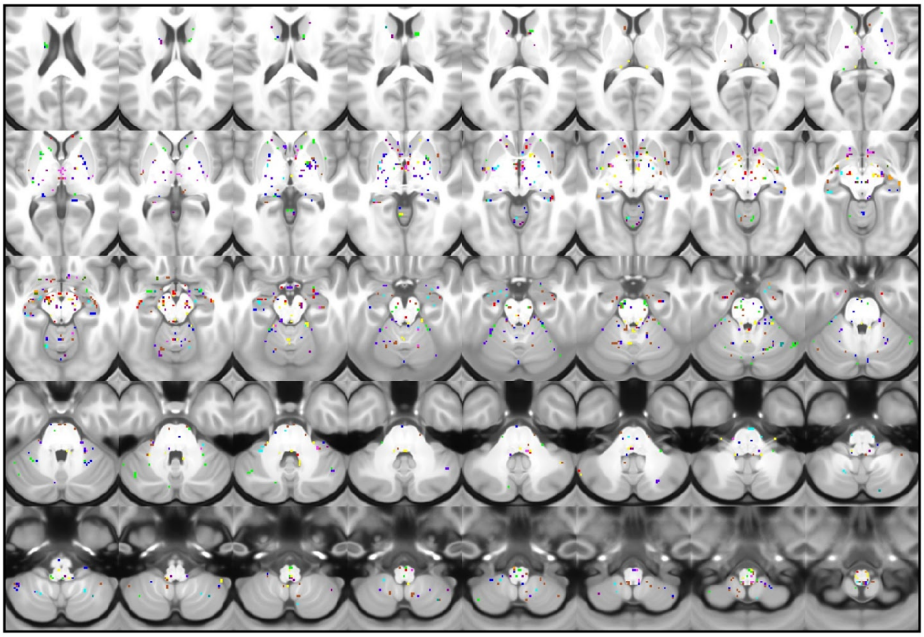
No. of Voxels in 1-Voxel and Asymmetrical 2 to 5-Voxel Clusters

	Voxel Count				
	1-voxel clusters	2-voxel clusters	3-voxel clusters	4-voxel clusters	5-voxel clusters*
Visual1	150	28	27	12	0
Visual2	113	32	24	12	15
Somatomotor	59	16	15	0	15
Cingulo-Opercular	66	24	12	4	0
Dorsal Attention	122	32	21	12	5
Language	9	0	3	0	5
Frontoparietal	98	30	9	8	5
Auditory	56	22	3	16	10
Default Mode	64	20	9	4	0
Posterior Multimodal	163	66	36	20	0
Unknown	26	10	9	0	0
Orbito-Affective	25	10	0	4	0
Total	**951**	**290**	**168**	**92**	**55**

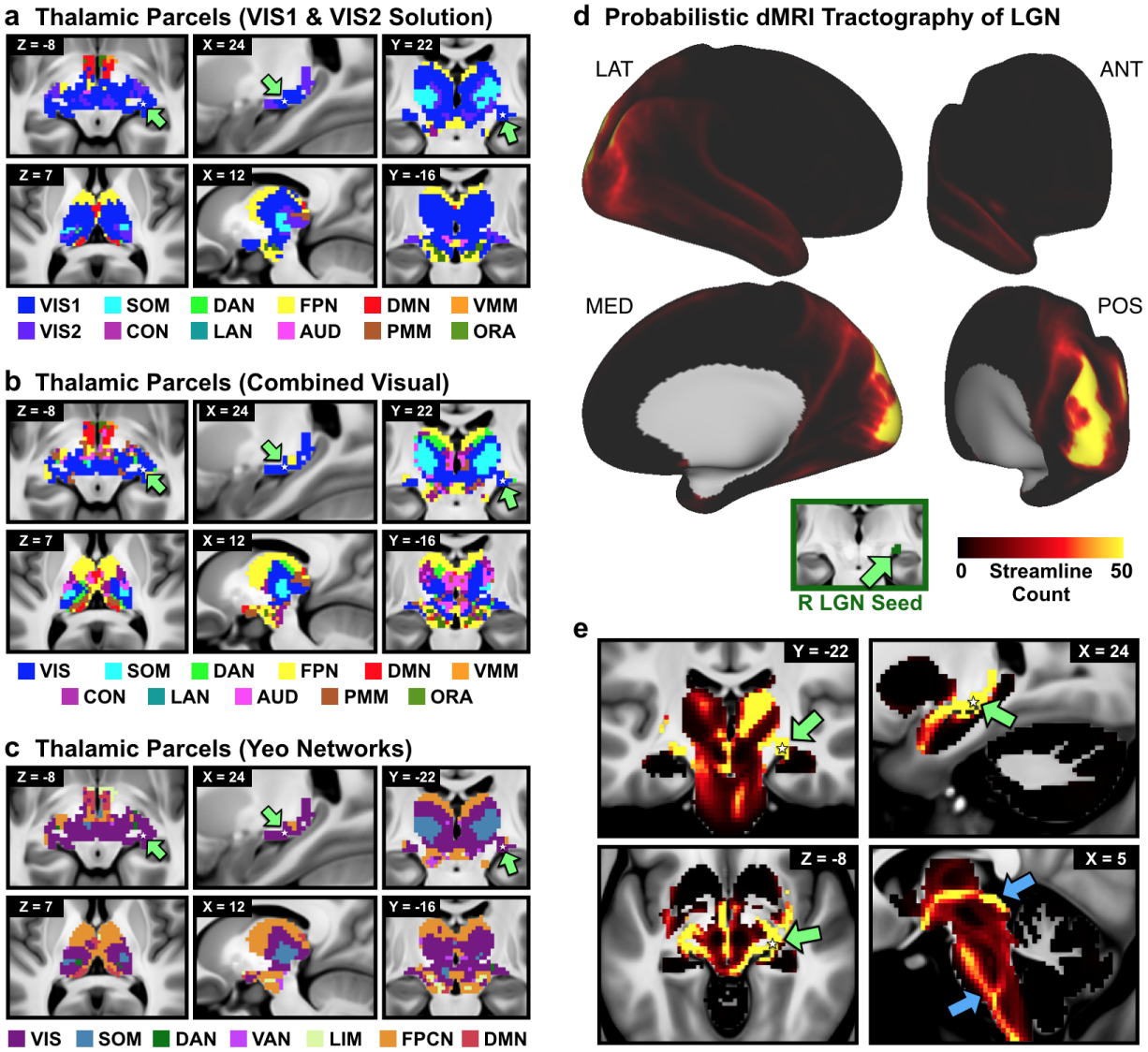
* not removed

b

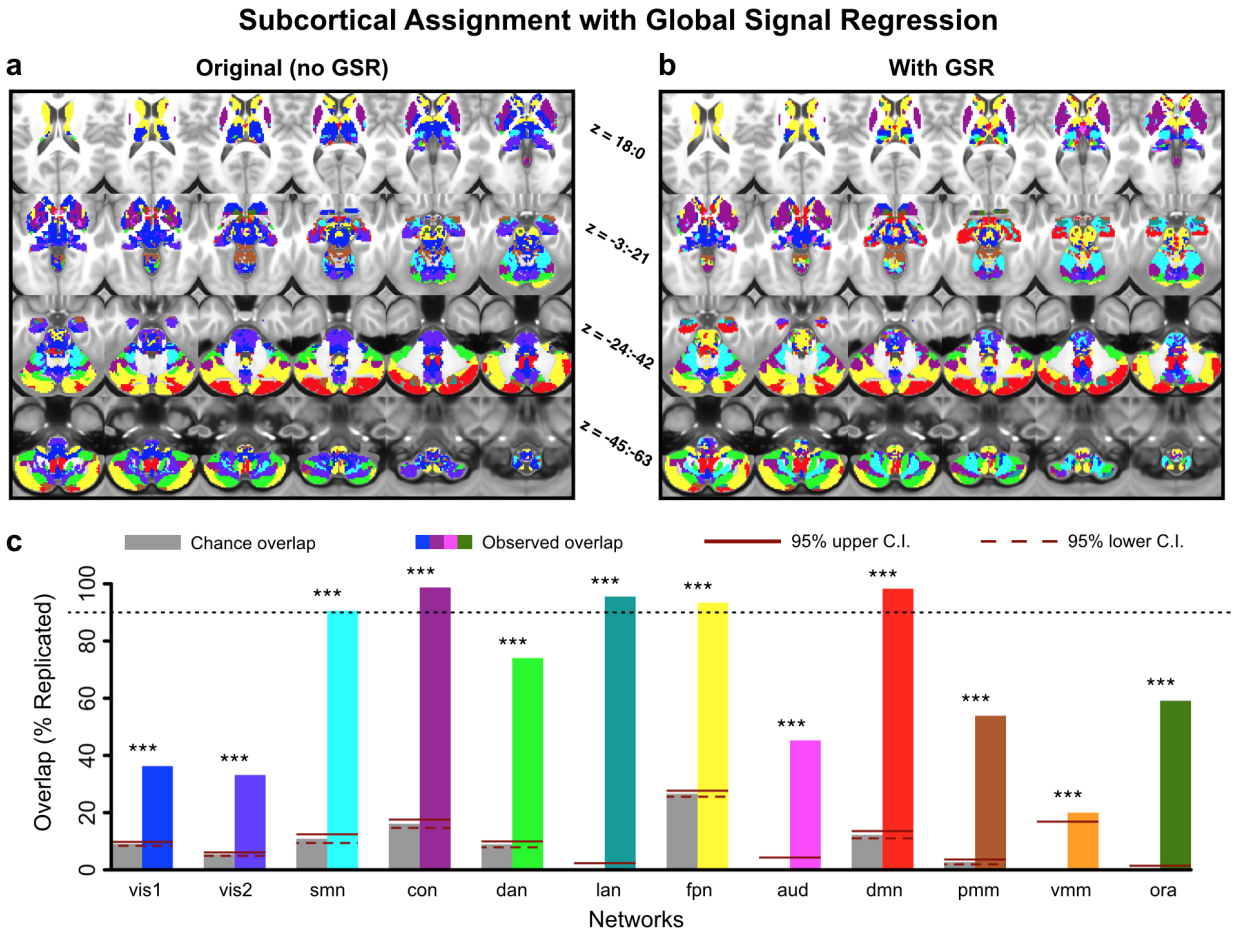
Map of Voxels Removed



Supplemental Figure S2. Cleanup of subcortical network assignment. We removed isolated single-voxel parcels that did not share a network assignment with any adjacent voxels, and parcels of size 2-4 voxels that did not have a counterpart with the same network assignment within a 2mm radius in the contralateral hemisphere. These removed voxels were later reassigned using nearest-neighbour interpolation. **A)** Total number of voxels removed by this process. We also identified 5-voxel parcels using the same criteria, but this flagged only a trivial number of voxels (55 voxels, or 0.17% of the total subcortex). **B)** Map of voxels removed (from parcels of size 1-4 voxels), colored by their original network.



Supplemental Figure S3. Thalamic network assignment. A) Network assignment of the thalamus and ventral diencephalon from the network partition described in the manuscript. Top row highlights the horizontal, sagittal, and coronal views of the lateral geniculate nucleus (LGN), indicated by green arrows. White stars mark the voxel seeded for structural connectivity in D and E. Bottom row shows cross-sectional view of the parcellation at different slices. **B)** Network assignment of the thalamus and ventral diencephalon, using the same method as in A but with an alternate cortical partition where VIS1 and VIS2 networks are combined into a single network. **C)** Network assignment of thalamus and ventral diencephalon using cortical network parcellation from Yeo et al. (2011). **D)** Diffusion MRI-derived probabilistic tractography (i.e. 'structural' connectivity) of the right LGN to right cortex. Tractography results were computed from diffusion MRI data obtained from 334 subjects. Inset shows right LGN seed, identified using the Jülich atlas (Bürgel et al., 2006; Eickhoff et al., 2005), similar coordinates also reported in (Linzenbold et al., 2011; Marx et al., 2004; Smith et al., 2009a). **E)** Diffusion MRI-derived probabilistic tractography (i.e. 'structural' connectivity) of the right LGN to subcortex. White stars mark the right LGN voxel from which connectivity was seeded. Connectivity was strongest between right LGN, other thalamic nuclei, and other visual processing regions, including the superior colliculus and brainstem nuclei (blue arrows). Results were similar for the left LGN. Abbreviations: LAT, lateral; MED, medial; ANT, anterior; POS, posterior.



Supplemental Figure S4. Subcortical network assignment using data with global signal regression (GSR). A) Original subcortical network assignment. **B)** Subcortical network assignment computed using data with GSR performed. **C)** Proportion of voxels in the original subcortical parcellation (without GSR) with the same network assignment in the version with GSR (see **Methods**). Gray bars indicate proportion of each network in the original version (without GSR) expected to overlap in the version with GSR by chance, given the total number of voxels in the subcortex. Colored bars indicate the observed overlap in each network between the two versions. Solid and dashed red lines indicate 95% upper and lower confidence intervals for chance respectively. The proportion of voxels with identical network assignments in both versions was significantly above chance for all 12 networks (p<0.05). Five of the networks (SMN, CON, LAN, FPN, DMN) were replicated at over 90% similarity in the data with GSR (black dotted line), indicating that they are highly stable.

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