**Online Methods**

**Subjects**

Three datasets acquired at different places were used in this work. The first one was used to study day-to-day variability of resting-state sessions from the same subject (dataset A). The second dataset (dataset B) is publicly available and is part of the Consortium for Reliability and Reproducibility (CoRR) (REF: <http://www.nature.com/articles/sdata201449>). We used this dataset to generalize the results to a larger number of subjects scanned in a different location. The third dataset (dataset C) was to classify both subjects and conditions (resting-state vs. free naturalistic viewing).

***Dataset A.*** This dataset has two parts. The first part (A1) is longitudinal and consists of resting-state fMRI sessions from 8 subjects (age 24-32, 6 female). 2 subjects (one male, one female) were not able to continue the study and were discarded. The other 6 subjects underwent scanning between 40 and 50 times along a period of 6 months. The second part of the dataset (A2) was acquired during the same period of time. A total 50 subjects (age 18-32, all female) were scanned during one rsMRI session using the same MRI sequences. Participants were free of psychiatric disorder according to personal interview (Mini-International Neuropsychiatric Interview REF) and had never suffered from a mental disease. The study was approved by the local ethics committee (Charité University Clinic, Berlin).

*Pre-processing*

The data was preprocessed using SPM5 (REF) and DPARSF (REF) after discarding the first 10 volumes of each session, and included: slice timing and head motion correction (6 parameters spatial transformation), spatial normalization to the Montreal Neurological Institute (MNI) template, and spatial filtering of 4 mm FWHM. The data was parcellated using the Automated Anatomical Labeling (AAL) atlas (REF) into 116 regions of interest (ROI). Linear trends were removed from the fMRI time courses before band-pass filtering (0.01 – 0.08 Hz). Participants were instructed to remain with their eyes closed and data acquisition had to be constrained to 5 min per scan due to experimental limitations.

***Dataset B.*** This dataset consists of 10 fMRI resting-state sessions acquired from 30 healthy participants every three days for one month (10-minutes length).

*Pre-processing*

The first 5 fMRI volumes were discarded in order to let the BOLD signal reach stability. The pre-processing pipeline included: slice-timing correction, motion correction, co-registration of the T1 anatomical image to the mean functional image, detrending, regression of 6 movement parameters, 5 PCA white matter and csf Compcorr, and spatial normalization to MNI coordinates. Scrubbing with Power 0.5 and linear interpolation was applied. Data was parcellated into 116 ROI (AAL), and time courses were band-pass filtered between 0.01 and 0.08 Hz. No global signal regression and spatial smoothing were applied.

***Dataset C.*** We used a third dataset to study the discrimination between subjects and conditions. In this case, a total of 22 subjects (age 20-31, 15 females) were scanned during rest with eyes opened and natural viewing condition. Volunteers were informed about the experimental procedures, which were approved by the Ethics Committee of the Chieti University, and signed a written informed consent.

Functional imaging was performed with a 3T MR scanner (Achieva; Philips Medical Systems, Best, The Netherlands) at the Institute for Advanced Biomedical Technologies in Chieti, Italy.

*In the resting state, participants fixated a red target with a diameter of 0.3 visual degrees on a black screen. In the natural viewing condition, subjects watched and listened to 30 minutes of the movie `The Good, the Bad and the Ugly' in a window of $24\times10.2$ visual degrees. Visual stimuli were projected on a translucent screen using an LCD projector, and viewed by the participants through a mirror tilted by 45 degrees. Auditory stimuli were delivered using MR-compatible headphones.*

*For each subject, 2 and 3 scanning runs of 10 minutes duration were acquired for resting state and natural viewing, respectively.* ***Only the first 2 movie scans are used here, to have the same number of time points for the two conditions (i.e., 20 minutes each)****.*

*Pre-processing*

*Data was preprocessed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK), including slice-timing and head-motion correction, co-registration between anatomical and mean functional image, and spatial normalization to MNI stereotaxic space (Montreal Neurological Institute, MNI) with a voxel size of $3 \times 3 \times 3$~mm$^3$.*

\added{The mean frame wise displacement \cite{Power\_NeIm\_2012} was measured from the fMRI data to estimate head movements. They do not show any significant difference across the rest and movie recordings ($p > 0.4$).} Furthermore, independent component analysis (ICA) was applied to the BOLD time series for the identification and removal of artifacts related to blood pulsation, head movement and instrumental spikes \cite{Sui\_NeIm\_2009}. This BOLD artifact removal procedure was performed by means of the GIFT toolbox (Medical Image Analysis Lab, University of New Mexico). No global signal regression or spatial smoothing was applied.

*Finally, mean BOLD time series were extracted from $N = 66$ regions of interest (ROIs) of the brain atlas used in \cite{Hagmann\_PB\_2008} for each recording session (subject and run); see Table~\ref{tab\_ROIs} for the complete list.*

------------------

\subsection{Data acquisition}

Functional imaging was performed with a 3T MR scanner (Achieva; Philips Medical Systems, Best, The Netherlands) at the Institute for Advanced Biomedical Technologies in Chieti, Italy.

The functional images were acquired using T2\*-weighted echo-planar images (EPI) with BOLD contrast using SENSE imaging. EPIs comprised of 32 axial slices acquired in ascending order and covering the entire brain (230 x 230 in-plane matrix, TR/TE=2~s/3.5~s, flip angle = 90$^\circ$, voxel size=$2.875 \times 2.875 \times 3.5$~mm$^3$). For each subject, 2 and 3 scanning runs of 10 minutes duration were acquired for resting state and natural viewing, respectively. **Only the first 2 movie scans are used here, to have the same number of time points for the two conditions (i.e., 20 minutes each)**. Each run included 5 dummy volumes - allowing the MRI signal to reach steady state and an additional 300 functional volumes that were used for analysis. Eye position was monitored during scanning using a pupil-corneal reßection system at 120~Hz (Iscan, Burlington, MA, USA). A three-dimensional high-resolution T1-weighted image, for anatomical reference, was acquired using an MP-RAGE sequence (TR/TE=8.1~s/3.7~s, voxel size=$0.938 \times 0.938 \times 1$~mm$^3$) at the end of the scanning session.

**Connectivity and estimates**

\subsection{Structural connectivity}

Anatomical connectivity was estimated from Diffusion Spectrum Imaging (DSI) data collected in five healthy right-handed male participants \cite{Hagmann\_PB\_2008, Honey\_PNAS\_2007}. The gray matter was first parcellated into the $N = 66$ ROIs, using the same low-resolution atlas used for the FC analysis. For each subject, we performed white matter tractography between pairs of cortical areas to estimate a neuro-anatomical connectivity matrix. In our method, the DSI values are only used to determine the skeleton: a binary matrix of structural connectivity (SC) obtained by averaging the matrices over subjects and applying a threshold for the existence of connections. The strengths of individual intracortical connections do not come from DSI values, but are optimized as explained below.

It is known that DSI underestimates inter-hemispheric connections \cite{Hagmann\_PB\_2008}. Homotopic connections between mirrored left and right ROIs are important in order to model whole-cortex BOLD activity \cite{Messe\_PCB\_2014}. Here we add all such possible homotopic connections, which are tuned during the optimization as other existing connections. This slightly increases the density of structural connectivity (SC) from 27\% to 28\%.

\subsection{Empirical functional connectivity}

For each of the two sessions of 10 minutes of rest and movie, the BOLD time series is denoted by $s\_i^t$ for each region $1 \leq i \leq N$ with time indexed by $1 \leq t \leq T$ ($T = 300$ time points separated by a TR=2 seconds). \added{We denote by $\bar{s}\_i$ the mean signal: $\bar{s}\_i = \frac{1}{T} \sum\_t s\_i^t$ for all $i$.} Following \cite{Gilson\_PCB\_2016}, the empirical FC corresponds to covariances calculated as:

\begin{eqnarray} \label{eq\_emp\_cov}

\widehat{Q}^0\_{ij} & = & \frac{1}{T-2} \sum\_{1 \leq t \leq T-1} (s\_i^t - \bar{s}\_i) (s\_j^t - \bar{s}\_j)

\ ,

\\

\widehat{Q}^1\_{ij} & = & \frac{1}{T-2} \sum\_{1 \leq t \leq T-1} (s\_i^t - \bar{s}\_i) (s\_j^{t+1} - \bar{s}\_j)

\nonumber

\end{eqnarray}

For each individual and session, we calculate the time constant $\tau\_x$ associated with the exponential decay of the autocovariance averaged over all ROIs:

\begin{equation} \label{eq\_tau}

\tau\_x = \frac{1}{N} \sum\_{1 \leq i \leq N} \frac{1}{\log(\widehat{Q}^0\_{ii}) - \log(\widehat{Q}^1\_{ii})}

\end{equation}

This is used to ``calibrate'' the model, before its optimization. Similar calculations are done for 2 TR.

\subsection{Model of cortical dynamics}

\added{The model uses two sets of parameters to generate the spatiotemporal FC:

\begin{itemize}

\item the local variability embodied in the matrix $\Sigma$ inputed individually to each of the $N = 66$ ROIs (see Table~\ref{tab\_ROIs} for the complete list) or jointly to ROI pairs (only for bilateral CUN, PCAL, ST and TT);

\item the network effective connectivity between these ROIs embodied by the matrix $C$, whose skeleton is determined by DTI (see details for structural connectivity above).

\end{itemize}}

\added{The rationale behind the use of spatially cross-correlated inputs (off-diagonal elements of $\Sigma$) in the model is to take into account for common sensory inputs to homotopic visual and auditory ROIs. Ideally, the model should be extended to incorporate subcortical areas and the existence of input cross-correlations inputs should be evaluated for all ROI pairs. However, this level of details is out of the scope of the present work and we constrain such input cross-correlations to 4 pairs of ROIs.

Another point concerns the use of individual EC skeletons or refinements of SC using graph theory for individual groups \cite{Arsigny\_MRM\_2006}, but we leave this for later work.}

Formally, the network model is a multivariate Ornstein-Uhlenbeck process, where the activity variable $x\_i$ of node $i$ decays exponentially with time constant $\tau\_x$ - estimated using Eq.~\eqref{eq\_tau} - and evolves depending on the activity of other populations: $\dd x\_i = \big( \frac{- x\_i}{\tau\_x} + \sum\_{j \neq i} C\_{ij} x\_j \big) \dd t + \dd B\_i$. Here, $\dd B\_i$ is \added{spatially} colored noise with covariance matrix $\Sigma$, with the variances of the random fluctuations on the diagonal and cross-correlated inputs corresponding to off-diagonal elements for CUN, PCAL, ST and TT (see Table~\ref{tab\_ROIs}).

In the model, all variables $x\_i$ have zero mean and their spatiotemporal covariances $Q^\tau\_{ij}$, where $\tau$ indicates time shift, can be calculated by solving the Lyapunov equation: $J Q^0 + Q^0 J^\transp + \Sigma = 0$ for $\tau = 0$; and then $Q^\tau = Q^0 \expm(J^\transp \tau)$ for $\tau > 0$.

Here $J$ is the Jacobian of the dynamical system and depends on the time constant $\tau\_x$ and the network effective connectivity: $J\_{ij} = \frac{-\delta\_{ij}}{\tau\_x} + C\_{ij}$, where $\delta\_{ij}$ is the Kronecker delta and the superscript $\transp$ denotes the matrix transpose; $\expm$ denotes the matrix exponential.

In practice, we use two time shifts: $\tau = 0$ on the one hand and either $\tau = 1$ or 2~TR on the other hand, as this is sufficient to characterize the network parameters.

\subsection{Parameter estimation procedure}

We tune the model such that its covariance matrices $Q^0$ and $Q^\tau$ reproduce the empirical FC, namely $\widehat{Q}^0$ and $\widehat{Q}^\tau$, with $\tau$ being either 1 or 2 TR.

\added{The uniqueness of this estimation follows from the bijective mapping from the model parameters $C$ and $\Sigma$ to the FC pair (FC0,FC1).

Despite the estimation of input cross-correlation, the essential steps are similar to the iterative optimization procedure described previously \cite{Gilson\_PCB\_2016} to tune the network parameters $C$ and $\Sigma$.} At each step, the Jacobian $J$ is calculated from the current value of $C$. Then, the model FC matrices $Q^0$ and $Q^\tau$ are calculated from the consistency equations, using the Bartels-Stewart algorithm to solve the Lyapunov equation.

\added{The difference matrices $\Delta Q^0 = \widehat{Q}^0 - Q^0$ and $\Delta Q^\tau = \widehat{Q}^\tau - Q^\tau$ determine the model error $E = \sum\_{i,j} (\Delta Q^0)^2 + \sum\_{i,j} (\Delta Q^\tau)^2$, which is the matrix distance between the model and the data observables}.

The desired Jacobian update is the matrix $\Delta J^\transp = (Q^0)^{-1} [\Delta Q^0 + \Delta Q^1 \expm(J^\transp \tau)]$, \added{which decreases the model error $E$ at each optimization step, similar to a gradient descent. The best fit corresponds to the minimum of $E$.} Finally, the connectivity update is $\Delta C\_{ij} = \eta\_C \Delta J\_{ij}$ for existing connections only; other weights are forced at 0. We also impose non-negativity for the EC values during the optimization.

\added{To take properly the effect of cross-correlated inputs into account, we adjust the $\Sigma$ update from the heuristic update in \cite{Gilson\_PCB\_2016}: $\Delta \Sigma = - \eta\_\Sigma (J \Delta Q^0 + \Delta Q^0 J^\transp)$.

As with weights for non-existing connections, $\Sigma$ elements distinct from the diagonal and cross-correlated inputs are kept equal to 0 at all times.}

In numerical simulations, we use $\eta\_C = 0.0005$ and $\eta\_\Sigma = 0.05$.

\added{To verify the robustness of the optimization with respect to the choice for ROIs with (spatially) cross-correlated inputs, we compared the tuned models with input cross-correlation for 1) CUN, PCAL, ST and TT; 2) CUN, PCAL, LING, LOCC, ST, TT and MT; 3) none. Although detailed estimates differ, the results presented in this paper are qualitatively observed for all three models. In practice, the model compensates the absence of input cross-correlations by overestimating the connections between the corresponding ROIs.} For simplicity, we only consider such inputs for putative primary sensory ROIs involved in the task here.

\added{The optimization code is available with the empirical data on \url{github.com/MatthieuGilson/EC\_estimation}. The discarded subjects in the present study are 1, 11 and 19, among the 22 subjects available (numbered from 0 to 21).}

**Similarity between sessions**

We used Pearson correlation coefficient (PCC) as a measure of similarity, both within- and between-subject. To compute the similarity between two sessions, each connectivity matrix C\_i was transformed into a vector v\_i by extracting the lower triangle for FC, and by applying the SC mask for EC. Each vector v\_i had a size of 1x6670 for FC data, and 1x4056 for EC (116 ROIs and 6,670 connectivity links for FC and 4,056 for EC). After vectorization, the values of all the links were z-scored (using the mean and standard deviation of each v\_i) and we computed the similarity between every pair of sessions in data set A1 (figure 2a). The within-subject similarity was obtained by computing the PCC between every possible pair of vectors, v\_i and v\_j (i!=j) from the same subject. For computing the between-subject similarity of data set A1 and B, one session per subject was randomly chosen and the similarity was obtained between all the different combinations of pairs of vectors (15 PCC for 6 subjects and 435 PCC for 30 subjects). This procedure was repeated 1,000 times. Figure 2.b shows the probability density function of the similarity after splitting into within- and between-subject the coefficients for both FC and EC. Data set A.2 was used as well to obtain another between-subjects similarity distribution (1225 PCC for 50 subjects).

**Dimensionality analysis**

To study visually how the data is spread over such a high-dimensional space, we applied PCA to extract the main dimensions reducing the original data. After applying PCA to the whole data set A1 (6 subjects, 40-50 sessions per subject) the first 6 components (PC1, 2, 3, and PC4, 5, 6) of both FC and EC measures, are plotted in figure 2.c. The silhouette coefficient was computed for each point in these clouds and plotted in figure 2.d. The reason for choosing only the first 6 PCs is because the mean silhouette coefficient of EC data reaches a maximum for this value, and then starts to decrease. The silhouette of FC data needs one or two more PCs to reach a maximum (sup.). The same method was applied to the data set B (30 subjects, 10 sessions per subject), and the maximum of the mean silhouette was at 30 PCs (supp). Both distributions of the silhouette, data set A1 with the first 6 PCs and data set B with the first 30 PCs, are plotted in figure 2.e.

**Classification of subjects**

Figure 3.a shows the classification procedure applied to identify subjects using connectivity measures and estimates. First, a fixed number of sessions per subject were extracted from each data set, FC and EC matrices. These matrices were vectorized as before and individually z-scored, using the mean and standard deviation of each v\_i. Then, the corresponding classifier (kNN or MLR) was trained using two different approaches: with and without applying PCA. The reason to use both approaches is because PCA is commonly applied in machine learning as a preprocessing step in order to reduce the computational load. Some studies have already applied a kNN classifier to identification of subjects without PCA (Finn, etc.), and we wanted to assess the possible benefit of this transformation in the classification performance. Finally, the parameters of the model were obtained (for the case of MLR classifier) and tested on the remaining sessions. We used data set A1 to study the effect of increasing the train set, as well as data set B to extend the results to a larger group of subjects. The same method was also applied to data set C. Figure 3.b shows the accuracy of both classifiers on the two data sets. The curves were obtained iterating over different sessions and subjects 100 times (mean and standard deviation are plotted).

**Extraction of most discriminative networks**

The study of the links (or edges) that drive the classification of both subjects and conditions, we used the dataset C.