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Impact of simulated lesions on communicability metrics of the brain structural network

Jennifer Andreotti[1], Kay Jann[1,2], Lester Melie-Garcia[1,3], Stéphanie Giezendanner[1], Thomas Dierks[1], and Andrea Federspiel[1]
[1]Department of Psychiatric Neurophysiology, University Psychiatric Hospital, Bern, BE, Switzerland, [2]Department of Neurology, University of California Los Angeles, Los angeles, California, United States, [3]Department of Neuroinformatics, Cuban Neuroscience Center, Havana, Havana, Cuba

PURPOSE: In the present study, communicability related metrics of brain structural networks of 19 healthy subjects were analyzed. Communicability is a wider measure of connectivity based on the idea that potentially any path between two nodes will contribute to the total flow of information ([1], [2]). In previous studies, communicability metrics were found to be useful to detect differences in the network organization of patients versus controls also in peripheral areas distant from the main lesion focus ([2], [3]). This suggests that communicability metrics may be more sensitive to reorganizational changes of the brain network following a lesion. The specific aim of this study was to assess the sensitivity of communicability related metrics by the use of simulated lesions modelled as random and targeted attacks to nodes and single edges respectively.

METHODS:

Data acquisition: Diffusion Tensor Imaging (DTI) was performed on a Siemens Trio 3T scanner using a spin echo (SE-) sequence (TR/TE=6800/93ms, matrix size=128×128, FOV 256×256 mm^2, 50 slices, slice thickness=2 mm, gap thickness=0 mm, pixel bandwidth 1346 Hz/pixel, max b-value 1300 s/mm^2,42 non-collinear directions). In addition, T1-weighted anatomical images were acquired with a 12-channel head coil (176 sagittal slices, slice thickness=1.0 mm, FOV 256×256 mm^2, TR/TE=7.92/2.48 ms, Flip angle=16°, inversion with symmetric timing (inversion time= 910 ms), fat saturation).

Network construction: Movement and eddy currents corrections were performed in FSL. After coregistration of diffusion weighted images with T1-weighted images an automated cortical parcellation was performed in FreeSurfer ('Destrieux' cortical atlas). The structures defined then served as ROIs for probabilistic fiber tracking in FSL. A connectivity map for each ROI was created starting from seeds placed in every voxel of the ROI considered (Tracking parameters: 5000 paths from each seed point, step size 0.5 mm, maximum trace length 500 mm and curvature threshold of ±80degrees). An index of connectivity was assigned to each brain voxel, representing the proportion of generated paths from the seed region that passed through it. For each subject, the undirected weighted network was created using 154 ROIs as nodes. An undirected edge a_{ij} between nodes i and j was established if a nonzero connectivity index was found to exist between the voxels of regions i and j. The edge weight was defined as the number of streamlines connecting the two ROIs corrected by ROIs' size.

Communicability measures: The communicability (Cm) between two nodes is given by a weighted sum of paths between the two nodes, where longer paths are down-weighted. In particular, the weighted Cm matrix of the connectivity matrix A can be computed as the exponential $exp(S^{-\frac{1}{2}}AS^{-\frac{1}{2}})$, where $S^{-\frac{1}{2}}$ is the diagonal matrix with elements $1/\sqrt{s\_i}$ and s_i is the strength of node i [2]. For binary Cm, the binary adjacency matrix is used and S is replaced by the identity matrix [1]. The concept of communicability betweenness (CBC) is specific to a node i and expresses the reduction in the total network communicability, when the node i and its connections are removed [4]. Additionally, the more common network metrics of degree (Deg), strength (S) and betweenness centrality (BC) were considered in the analysis. Weighted metrics are denoted by ^{W}.

Targeted and random attacks: a lesion in the network was modeled as a partial or complete removal of a node or an edge. In binary lesions the damaged connections were removed, while in weighted lesions weights of the damaged connections were reduced. A targeted attack denoted a lesion in which the attack site (nodes or edges) was selected with a specific strategy (for example high degree, high centrality), while in a random attack the lesion site was selected randomly [5]. In addition, "Single attack" strategy denoted the strategy in which network metrics were recomputed after each attack to select the next lesion site. In opposition, in the "Hubs attack" strategy the order of attacks is set only once.

On one side, for every type of lesion, the sensitivity of the different metrics of the network was computed and compared. In particular, the effect of lesions was assessed in the nodes directly affected, in their direct neighbors and in more peripheral nodes. On the other side, different criteria to select the target (Deg, BC, Cm, CBC) are compared by evaluating the reduction in the weighted global efficiency of the network: the criteria that causes the larger decrease in efficiency is the best one in detecting nodes sensitive to lesions. Decay curves for different target selection criteria were compared using permutation tests on the set of curves with the sum of differences as statistic.

RESULTS: Overall Single attack strategies affected more strongly the global efficiency of the network (Figure 1), with BC^W and Cm^W being the most effective strategies for target selection. Remarkably, Hubs - Cm^W was similarly effective. In particular, the efficiency decay curve obtained by Hubs - Cm^W was not significantly different from Single attack - BC^W (Perm test: p<0.33, n.s.), but it was from all Hubs strategies (Perm test: p<0.012 BC^W-Hubs, p<0.016 Single-CBC). Analyses on the sensitivity of metrics in the case of attacks to the connector hubs showed that Cm is affected similarly over all nodes. For metrics of centrality, an increase of centrality of the peripheral nodes was found (Figure 2). BC was also increased for neighbor nodes, while CBC of neighbor nodes was slightly decreased.

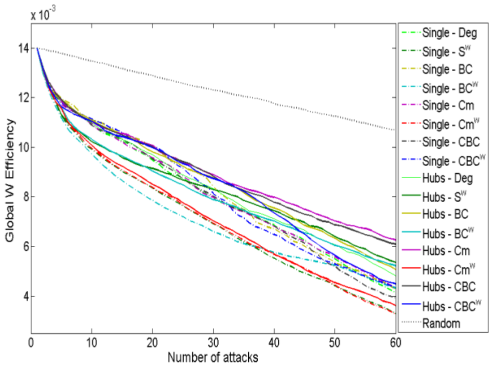

Figure 1: comparison of strategies for target selection.

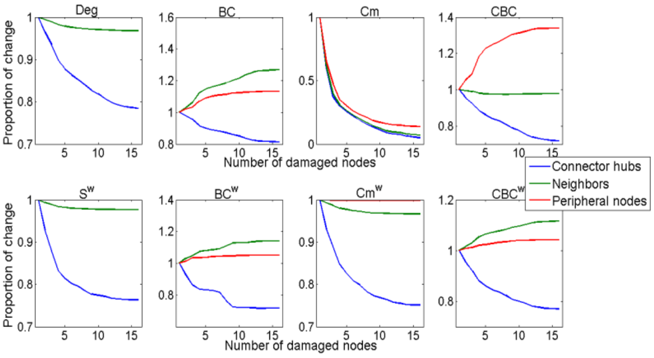

Figure 2: sensitivity of the metrics in the case of nodes lesions.

CONCLUSION: Our analysis showed that metrics related to communicability were differently sensitive to lesions. In particular, Cm^W was found to be a sensitive measure to select targets for attacks. In addition, the high increase of CBC in peripheral nodes and the changes in Cm over the whole network confirmed that communicability metrics are sensitive to lesions also in regions distant from the main lesion focus. Overall, our results confirmed that communicability metrics are an interesting tool to study the effects of lesions and further analyses on single nodes may enable to better understand the mechanisms of reorganization following brain damage.

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