Maximum weight-dependent navigability on human brain connectomes

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The brain exists in a 3D Euclidean space and, therefore, connectomes are spatially embedded networks whose architecture has not only been shaped by communication needs throughout evolution, but also by physical constraints. As a result, geometry is a crucial factor to consider when studying communication processes on brain networks.

Historically, brain network communication has focused on optimal routing, which proposes that information travels through topological shortest paths. However, this approach requires each element of the nervous system to have full knowledge of the topology of the network and this assumption is highly unlikely in a physiological system [1]. Alternatively, more decentralized routing protocols that take advantage of the geometric nature of the brain have been proposed. One of these methods is the greedy routing, which is guided by a local rule that sends information to the connected region closest in distance to a desired destination. Several studies have used geometric distances to guide navigation on brain networks [2, 3] and have shown that combining topology and geometry can lead to near-optimal decentralized communication.

In this work, we introduce a framework to explore decentralized routing protocols that combine the weighted topology of the human connectome and its spatial embedding. More specifically, we explored a continuous spectrum of stochastic routing protocols, having the greedy routing strategy and a weight-biased random walk at the opposite extremes, on two cohorts of real human connectome networks.

In our framework, messages are preferentially sent along paths with larger connection weights and to nodes closer in space to the target node. This accounts for the expectations that messages have more chances to go through channels with more nerve fibers and that nearby nodes are connected with higher probability. We implemented a probability of transition in which distances obtained from weights and Euclidean distances are balanced using a tuning parameter λ [4]. Namely, the transition probability from node i to its neighbour j when going to target t is

$$P_\lambda(j\,|i\;t) = \exp(-(\lambda \cdot d^{\mathrm{e}}_{jt} + (1-\lambda)\cdot d^{w}_{ij}))\frac{1}{Z_i^t}, \qquad (1)$$

where $Z_i^t = \sum_j \exp(-(\lambda \cdot d^{\mathrm{e}}_{jt} + (1-\lambda)\cdot d^{w}_{ij}))$ is the normalization factor, d^{e} is the Euclidean distance between the centers of the regions, and $d^w_{ij} = \ln(1/w_{ij})$, where w_{ij} is the weight of the connection.

Since probabilistic procedures can take excessively long paths before reaching the destination we applied a time-out (measured in maximum number of steps) after which we suppose the message has faded before reaching the target. We studied two standard metrics widely employed to assess the efficiency of greedy routing navigation: the success rate –proportion of paths that reach the target successfully, when considering all possible source/target pairs– and the average stretch –ratio between the number of links in the path and the number of links in the topological shortest path between the source and the target, averaged over all successful paths.

We found that there is an intermediate region in this spectrum, a sweet spot, in which connectomes become maximally navigable, achieving full communication efficiency. Moreover, we found that in this region weights, topology and distances are coupled in such a way that information transmission not only is maximally efficient but also robust even under severe perturbation.

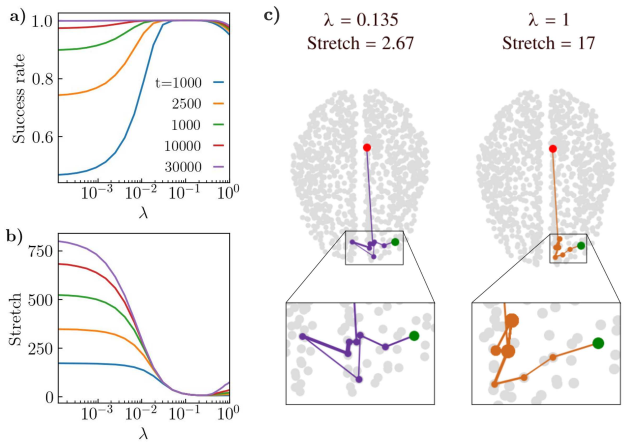

Fig. 1. **a, b)** Success rate and stretch respectively. Each curve shows the outcome for a specific value of time-out. **c)** Path taken from ROI 154, in red, to ROI 20, in green, for a value of λ in the sweet-spot region (in purple), and when considering only distances (in orange). In the insets the size of the nodes is proportional to the number of times the message visits them.

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