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On the robustness of consciousness neural correlates

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Abstract. According to dynamic core hypothesis, integration and differentiation are main properties of consciousness. Hence, we expected that the consciousness neuronal correlate covers these properties in structural level. These properties could be captured in small-worldness properties, i.e. high clustering coefficient and low path-length. Thalamocortical (TC) loop and cortex are two main candidates for Neural Correlates of Consciousness (NCC). We studied small-worldness in these systems. For this purpose, we calculated clustering coefficients, characteristic path lengths and their robustness against lesions. We simulated lesions in two ways: eliminating connections, and deleting nodes. We used anatomical connections of TC and cortex of macaque from the CoCoMac neuroinformatic database. Our results show that: 1) Lesions causes an increase in path length and decrease in clustering coefficient which cause the destruction of the integration and segregation capabilities of brain network; 2) Deleting the connections is more destructive than deleting the nodes; 3) During high levels of lesions, the thalamo-cortical connections are more important than cortico-cortical connections in the sense of clustering coefficient. In terms of path-length, during high levels of nodes' lesions, the thalamo-cortical connections are more important than cortico-cortical connections, while during edges' lesions cortico-cortical connections are more important than thalamo-cortical connections

1. Introduction

The brain contains a large number of connected neurons with specific functions. As a result of sophisticated interaction of these neurons, high level phenomena, such as cognition, emerge. These characteristics are enough to consider the brain a wonderful complex network [1].

One of the key features in complex networks is their connectional topology, which led to the introduction of the concept of small-worldness by Watts and Strogatz [2]. After their pioneer work, others showed that many complex social and biological networks are small-world [3-5]. The main feature of small-world networks is the simultaneous occurrence of high clustering coefficient and low path length. This property implies that small-world networks are segregated and integrated. In the brain, segregation is the ability to specialize processing in interconnected groups of brain regions, and one good measure for segregation is the clustering coefficient. Integration is the ability to unite specialized information from different brain regions, and one good measure for this concept is characteristic path length. Shorter paths show a stronger potential for integration.

According to the Dynamic Core Hypothesis (DCH), since conscious experiences are segregated and, at the same time, differentiated, their neural correlates should also have these characteristics at a structural level. These two properties could be captured based on small-world properties, i.e. high clustering coefficient and low path-length [6,7]. Therefore, the importance

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of evaluating small-worldness in the Neural Correlates of Consciousness (NCC) is obvious [8].

There are two main candidates for NCC: Thalamo-Cortical (TC) loop, and the cortex. Sporns and Zwi studied the small-worldness of the cortex [9]. In the current study, we used a network theory approach to study small-worldness in the thalamo-cortical loop, including the robustness of small-world characteristics in this system and its subset, cortex. For this purpose, we calculated clustering coefficients, characteristic path lengths and their robustness against lesions. We simulated lesions in two ways: eliminating connections in the network (which corresponds to lesions of the white matter), and deleting nodes (which corresponds to lesions of different brain regions) [10]. Studying robustness against lesions is helpful in understanding consciousness disorders in some diseases like Alzheimers (which is probably analogous to brain nodal lesions) and autism (which is claimed to be analogous to connection lesions) [11-13].

2. Methods

2.1. Dataset

In this study, we used anatomical connections of the TC and cortex of macaque, which is part of the network constructed by Modha and Singh [14] from the CoCoMac neuroinformatic database [15]. This included 383 regions of the cortex, thalamus, and basal ganglia. They used the connectivity information of the whole brain, but we focused on TC and cortex connections. For this purpose, we selected connections between the thalamus and the neocortex [14]. It means that those edges are selected whose source and destination lie in the thalamus or neocortex. Hence, a 253*253 binary connection matrix (with 253 nodes and 3644 edges, including cortico cortical, thalamo-cortical, cortico-thalamic and thalamo-thalamic connections) is constructed. The nodes with indices 1 to 73 represent thalamus regions (with 10 links as thalamo-thalamic connections, and 1181 thalamo-cortical and cortico-thalamic connections), and nodes with indices 74 to 253 represent cortex regions (with 2453 connection as cortico-cortical connections). The details of regions used in this study are presented in [16].

2.2. Lesion simulation

In this study, we make two types of lesion in the network: lesions to the nodes by eliminating nodes randomly, and lesions to the edges by deleting edges randomly. For the TC loop, we also consider two different cases: inserting lesions into whole TC elements (nodes or edges) or confining the lesions to the cortex part of the TC and then assessing the TC loop. We made different levels of lesions by deleting a different number of edges or nodes. The range of deletions includes 10% to 90% destruction of the corresponding network. It is worth noting that each of the experiments have been done 100 times for different randomly destructed nodes or edges. Also, in order to have a proper evaluation, all simulations are also done for random networks with the same size as the original network.

2.3. Network analysis

High "clustering coefficient" (similar to regular networks) and low "characteristic path length" (similar to random networks) are two key features of small-world networks. These two attributes give small-world networks some advantages in the processing and transmission of information [2].

A node's cluster index, $\gamma(v)$, is the ratio of existing connections among the b_v neighbors to the maximal possible number of such connections, $(b_v^2 - b_v)$. The average of all node cluster indices is called the clustering coefficient, γ, of the graph:

$$\gamma = \frac{1}{n}\sum_{v}\gamma(v) = \frac{1}{n}\sum_{v}\frac{2t_v}{b_v(b_v-1)}, \quad (1)$$

where t_v is the number of triangles around node v, and n is the number of nodes.

A "path" is defined as an ordered succession of distinct edges, which link source node j to target node i, and the number of distinct directed edges in a path is called the "path length". The "characteristic path length" (λ) of a graph is the average length of the shortest path [17]:

$$\lambda = \frac{1}{n}\sum_{i}L_i = \frac{1}{n}\frac{\sum_{j,j\neq i}d_{ij}}{n-1}, \quad (2)$$

where L_i is the average shortest path length between node i and all other nodes, and d_{ij} is the shortest path length between nodes i and j.

In this paper, we used Matlab 7.8 for network analysis, and for calculating the clustering coefficient and path length, Brain Connectivity Toolbox (BCT) is used [18].

3. Results

In order to evaluate the small-worldness of networks, clustering coefficient (Γ) and characteristic path length (Λ) are used [2]. We computed these characteristics for the TC loop (Table 1). The corresponding values for random and lattice (regular) networks are also presented in this table. These results show that since the TC loop gamma and lambda are between the corresponding values in random and lattice networks, TC is a small-world network. In Figure 1, the effects of node lesions on the clustering coefficient in TC loop (a) and cortex (b) are illustrated with their error bars. It

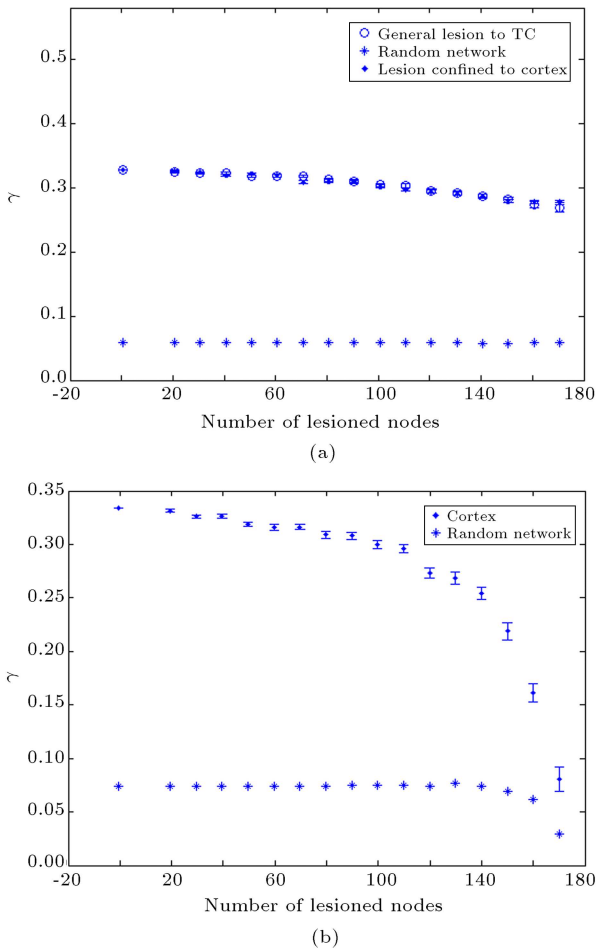

Figure 1. The effect of node lesions on clustering coefficient in TC loop (a) and cortex (b). In (a), the dots show the results of confining the lesions to the cortex, the circles show the results for a general condition, in which lesions are spread throughout the whole TC loop, and stars show the results of a random network with the same size as the original network.

Table 1. Characteristic path length and clustering coefficient for TC loop and its corresponding random and lattice networks.

	Random network	TC loop	Lattice network
Γ	2.349	2.497	11.875
Λ	0.0578	0.319	0.708

is obvious that lesions cause a slight decay in gamma pattern in the TC loop. In the cortex, however, the decay is remarkable for higher levels of lesion.

Figure 2 shows the effect of node lesions on the characteristic path-length (lambda) in TC loop (a) and cortex (b). It is observed that lesions in TC cause a little rise in the lambda. However, in the cortex, as the lesion amount exceeds 140 nodes, lambda drops suddenly. It seems that deleting nodes (which also clears its connections) converts the network to a smaller one, but, as the characteristics of the new network are

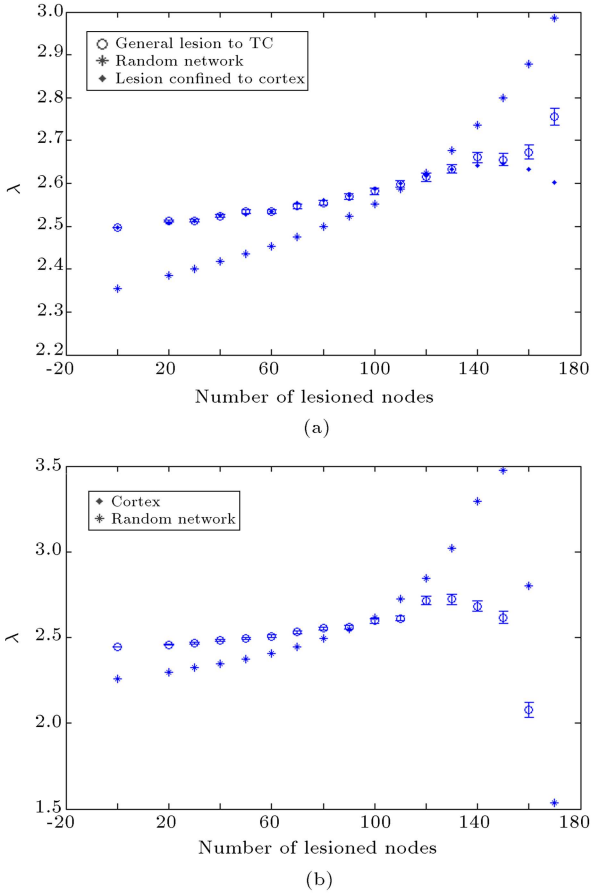

Figure 2. The effect of node lesions on characteristic path length in TC loop (a) and cortex (b). In (a), the dots show the results of confining the lesions to the cortex, the circles show the results for a general condition, in which lesions are spread throughout the whole TC loop, and stars show the results of a random network with the same size as the original network.

improved, we can conclude that this new network has some improved features also.

In Figure 3, the effect of edge lesions on gamma in TC loop (a) and cortex (b) is illustrated. It is obvious that the lesion causes a drop in gamma and, as the lesion percentage increases, gamma decreases further, in both the TC and cortex. As this figure shows, for higher levels of lesions, narrowing the lesion of the TC loop to the cortex has less effect on gamma than when the lesions are applied randomly on the whole TC loop.

Figure 4 shows the effect of edge lesions on lambda in TC loop (a) and cortex (b). The lesion causes a rise in lambda and, as the lesion percentage increases, lambda increases further, in both the TC and cortex.

4. Discussion

In this work, we first studied the small-worldness of the TC loop as one of the main suggested neural

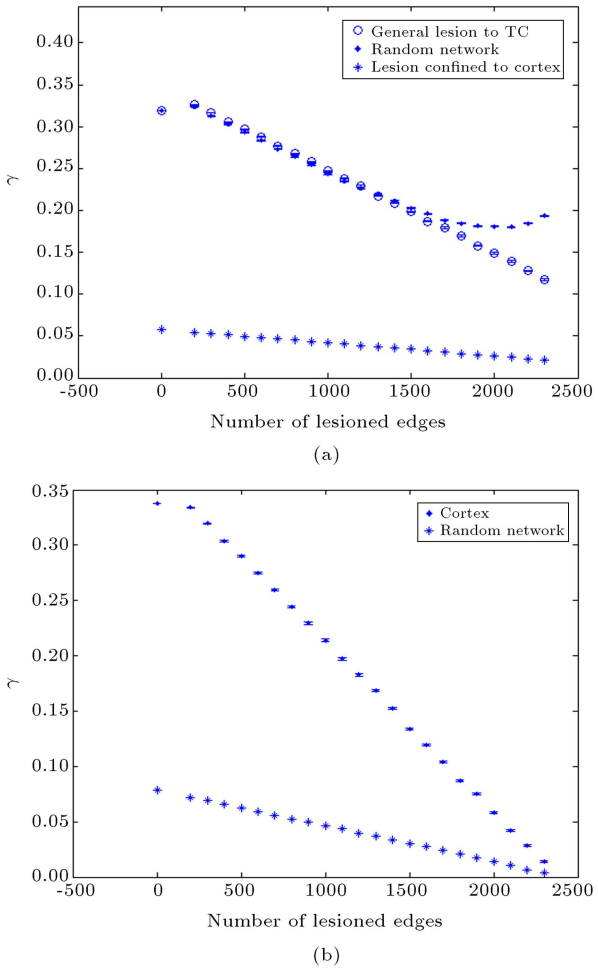

Figure 3. The effect of edge lesions on clustering coefficient in TC loop (a) and cortex (b). In (a), the dots show the results of confining the lesions to the cortex, the circles show the results for a general condition, in which lesions are spread throughout the whole TC loop, and stars show the results of a random network with the same size as the original network.

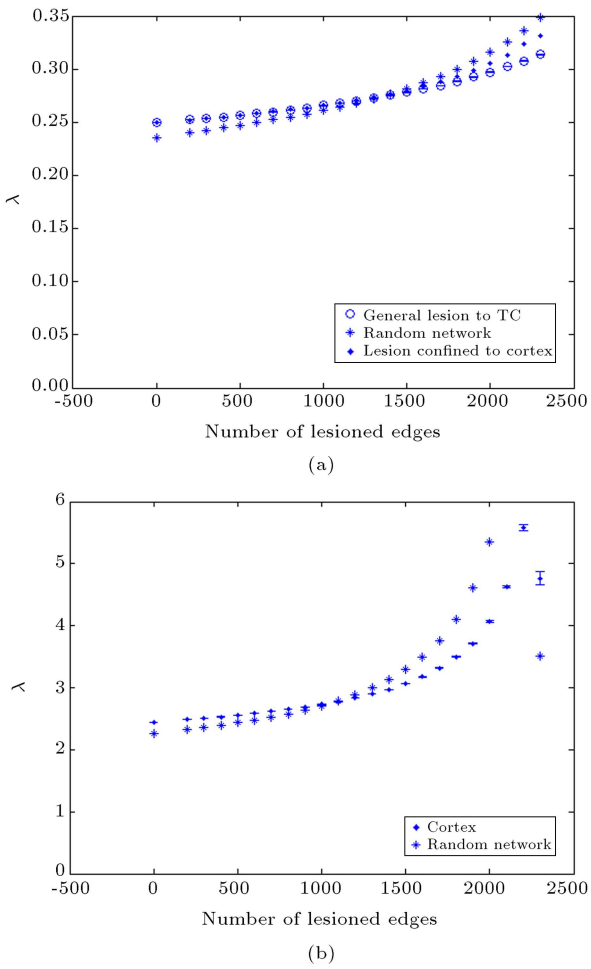

Figure 4. The effect of edge lesions on characteristic path length in TC loop (a) and cortex (b). In (a), the dots show the results of confining the lesions to the cortex, the circles show the results for a general condition, in which lesions are spread throughout the whole TC loop, and stars show the results of a random network with the same size as the original network.

correlates of consciousness. In previous studies, the small-worldness of the cortex, as the other strong candidate neural correlate of consciousness, has been shown [9,16]. The results of the current study show that the TC is also small-world (see Table 1).

Then, the robustness of the TC loop and cortex (as a subsystem of the TC loop) against lesions was studied. For this purpose, we simulated lesions in two ways: Deleting the edges randomly and deleting the nodes randomly. Our results suggest that:

- Deleting nodes leads to a decrease in clustering coefficient, both in the TC loop and cortex. However, this decrement is smaller than when the lesion is applied to the edges (see Figures 1 and 3).
- Deleting nodes increases path length slightly, both in the TC loop and cortex; this is in accordance with [19]. This increment is smaller than when the lesion is applied to the edges. It means that there are some nodes in the brain network which are not involved in shortcuts and, hence, their deletion does not affect path length remarkably (see Figures 2 and 4).
- When the edge lesions in the TC are severe and confined to the cortex, the decrease in clustering coefficient is less than when the lesions are spread through the whole network. This shows that the connections between the cortex and thalamus are more effective on the clustering coefficient than the connections between different cortical regions (see Figure 3(a)). It seems that the cortico-thalamic connections play a major role in brain network segregation. In other words, structural segregation is not restricted to cortical regions and the important role of the thalamus may not be ignored in this regard.

Table 2. The slope of variations in linear parts of the Λ and Γ in the TC and cortex, and their corresponding random networks, while producing lesions in nodes and edges. Standard deviations of slopes are shown in parentheses.

Network	Lesioning nodes	Lesioning edges
	Slope (SD)	Slope (SD)
Γ_{TC}	-0.06 (0.0028)	-0.24 (0.005)
$\Gamma_{\text{randomized TC}}$	-0.0028(0.0028)	-0.03 (0.0008)
Γ_{cortex}	-0.027 (0.006)	-0.12 (0.005)
$\Gamma_{\text{randomized cortex}}$	0 (0.002)	0 (0.001)
Λ_{TC}	0.23 (0.01)	0.7 (0.013)
$\Lambda_{\text{randomized TC}}$	0.63 (0.02)	1.2 (0.06)
Λ_{cortex}	0.25 (0.01)	2.6 (0.03)
$\Lambda_{\text{randomized cortex}}$	0.58 (0.033)	3.9 (0.037)

In an overview, the main points of this study are: 1) Clustering coefficient and characteristic path length are fairly robust against the destruction of network nodes. In contrast, deleting the connections is more destructive than removal of the nodes (Table 2). In this table, in order to cancel the default slope because of node or edge removal, we calculated the slopes for the random network in each of the above cases. All the slopes are calculated by normalizing a number of compartments, which are removed by their maximum values, because the numbers of nodes and edges are not equal. This shows that lesions on connections in the brain is more dangerous than lesions on the brain local regions; 2) During severe lesions to the nodes, the thalamo-cortical connections are more important than cortico-cortical connections in the sense of small-worldness (integration and segregation), because when the TC lesions are restricted to the cortex, the defections to path length and clustering coefficient are larger and, when the lesion is applied to edges, the opposite effect is seen. It seems that, in terms of clustering coefficient, thalamo-cortico-thalamic connections are more important than cortico-cortical connections in producing a robust small-world network in the brain, which could be considered a strong candidate for NCC. Surely, more studies from multiple neuroscience methodologies are needed to infer precisely in this regard [20].

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References

1. Bullmore, E. and Sporns, O. "Complex brain networks: graph theoretical analysis of structural and functional systems", *Nat Rev Neurosci.* (2009).
2. Watts, D.J. and Strogatz, S. "Collective dynamics of 'small-world' networks", *Nature*, pp. 440-442 (1998).
3. Cancho, R.F. and Solé, R.V. "The small world of human language", *Proceedings of the Royal Society of London. Series B: Biological Sciences*, pp. 2261-2265 (2001).
4. Wagner, A. and Fell, D.A. "The small world inside large metabolic networks", *Proc. Biol. Sci.*, pp. 1803-10 (2001).
5. Mislove, A., Marcon, M., Gummadi, K.P., Druschel, P. and Bhattacharjee, B. "Measurement and analysis of online social networks", In *Proceedings of the 7th ACM SIGCOMM Conference on Internet Measurement*, ACM, pp. 29-42 (2007).
6. Tononi, G., Sporns, O. and Edelman, G.M. "A measure for brain complexity: relating functional segregation and integration in the nervous system", *Proc. Natl. Acad. Sci.*, USA, pp. 5033-5037 (1994).
7. Tononi, G. and Edelman, G.M. "Consciousness and complexity", *Science*, pp. 1846-1851 (1998).
8. Seth, A. "Explanatory correlates of consciousness: Theoretical and computational challenges", *Cognitive Computation*, **1**(1), pp. 50-63 (2009).
9. Sporns, O. and Zwi J.D., *The Small World of the Cerebral Cortex*, pp. 1539-2791 (2004).
10. Kaiser, M., Martin, R., Andras, P. and Young, M.P. "Simulation of robustness against lesions of cortical networks", *European Journal of Neuroscience*, pp. 3185-3192 (2007).
11. Zhao, X., Liu, Y., Wang, X., Liu, B., Xi, Q., Guo, Q., Jiang, H., Jiang, T. and Wang, P. "Disrupted small-world brain networks in moderate Alzheimer's disease: A resting-state fMRI study", *PloS One* (2012).
12. Kleinhans, N.M., Richards, T., Sterling, L., Stegbauer, K.C., Mahurin, R., Johnson, L.C., Greenson, J., Dawson, G. and Aylward, E. "Abnormal functional connectivity in autism spectrum disorders during face processing", *Brain*, pp. 1000-1012 (2008).
13. Uhlhaas, P.J. and Singer, W. "Neural synchrony in brain disorders: relevance for cognitive dysfunctions and pathophysiology", *Neuron*, **52**(1), pp. 155-168 (2006).
14. Modha, Ds. and Singh, R. "Network architecture of the long-distance pathways in the macaque brain", *Proc. Natl. Acad. Sci.* USA, **107**, pp. 13485-90 (2010).
15. Kötter, R. "Online retrieval, processing, and visualization of primate connectivity data from the CoCoMac database", *Neuroinformatics*, **2**(2), pp. 127-144 (2004).
16. Bakouie, F., Gharibzadeh, S. and Towhidkhah, F. "A network theory view on thalamocortical loop", submitted to *Neurocomputing*.
17. Rubinov, M. and Sporns, O. "Complex network measures of brain connectivity: uses and interpretations", *Neuroimage*, **52**(3), pp. 1059-1069 (2010).

18. Sporns, O., Rubinov, M., Adachi, Y., Avena, A., Bassett, D., et al. *Brain Connectivity Toolbox (BCT)*, http://www.brain-connectivity-toolbox.net.

19. Sporns, O., Chialvo, D.R., Kaiser, M. and Hilgetag, C.C. "Organization, development and function of complex brain networks", *Trends in Cognitive Sciences*, **8**(9), pp. 418-425 (2004).

20. Young, M.P., Hilgetag, C.C. and Scannell, J.W. "On imputing function to structure from the behavioural effects of brain lesions", *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, **355**(1393), pp. 147-161 (2000).

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