上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

大脑神经网络

——结构、功能与应用

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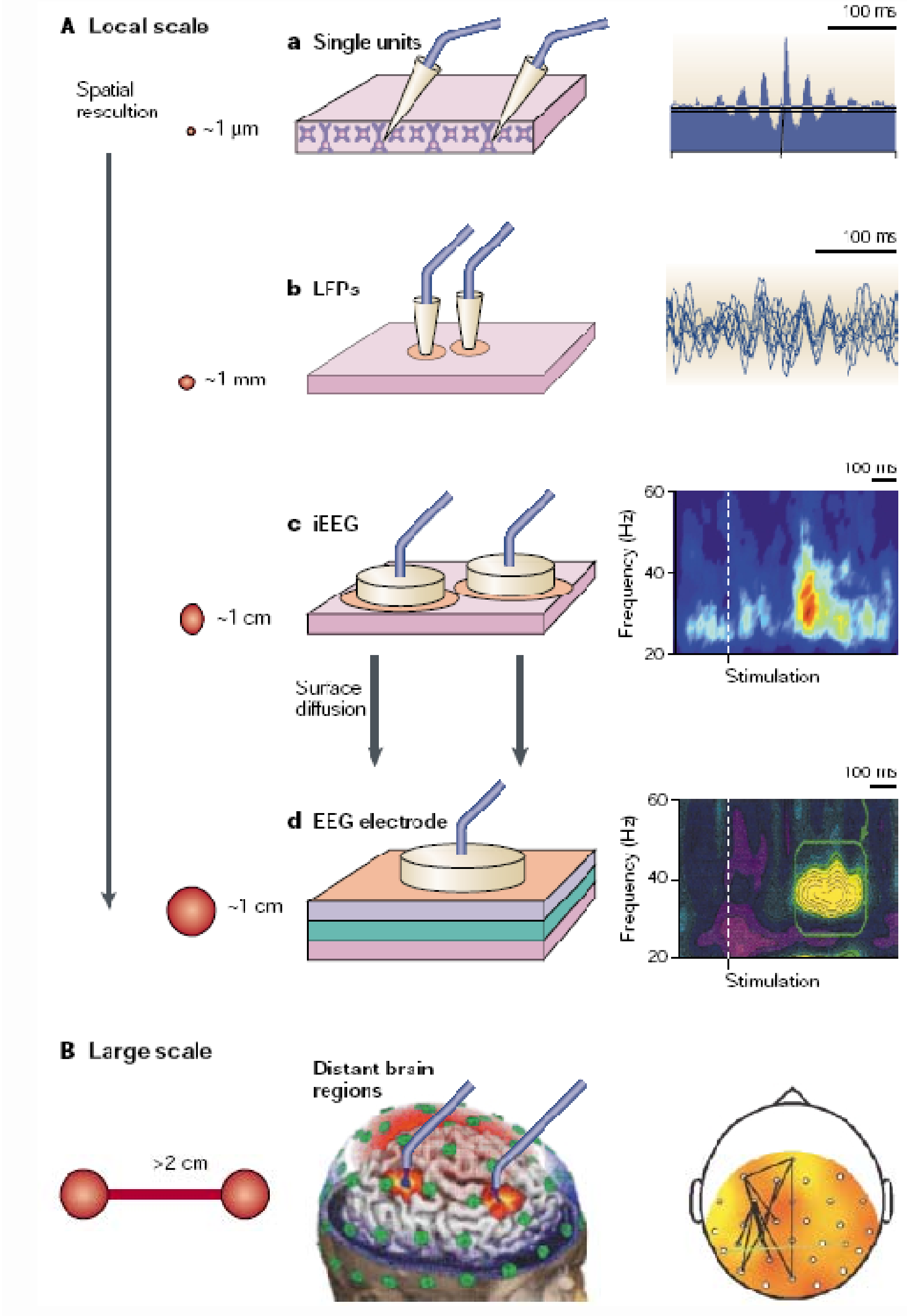
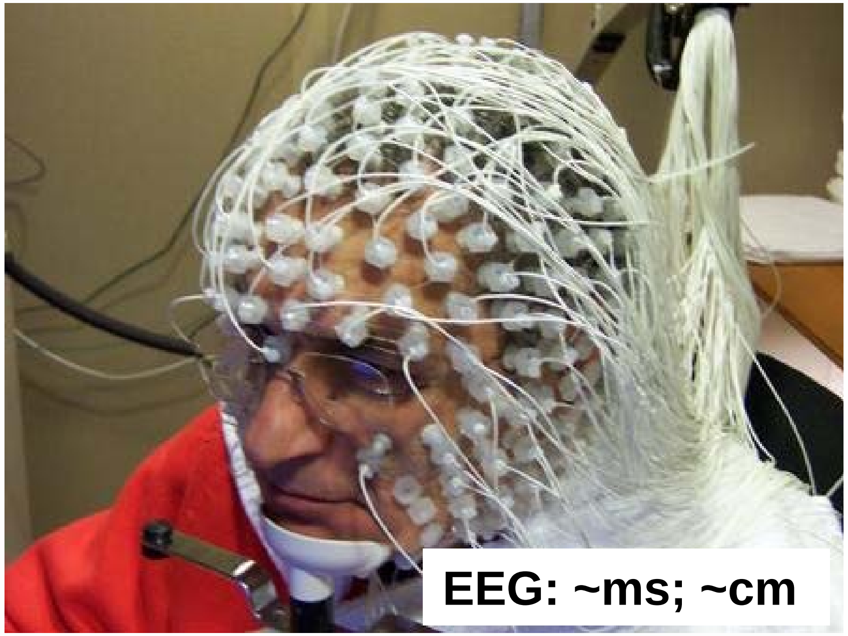
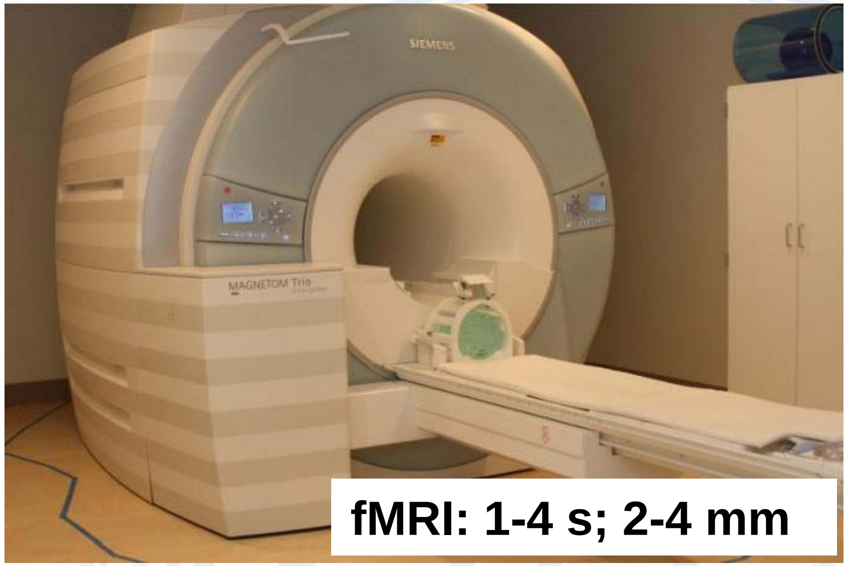
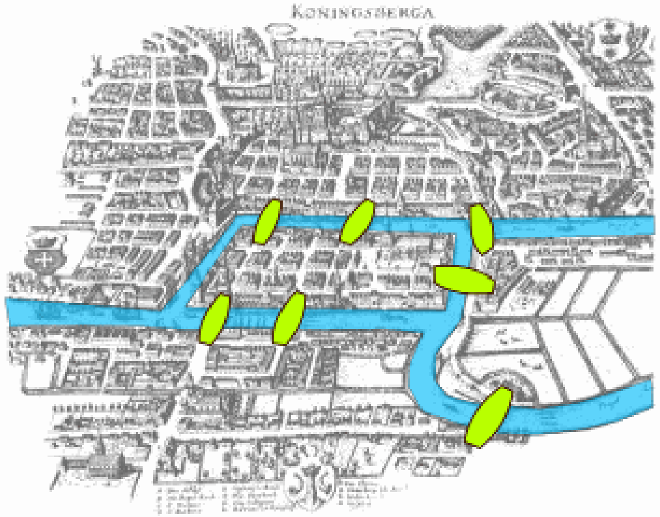




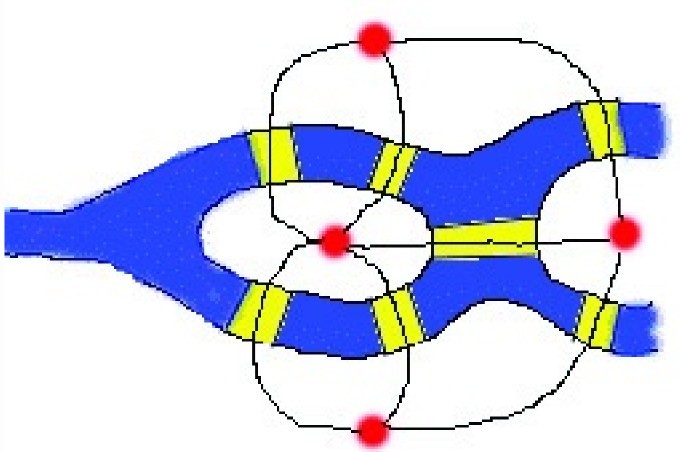


(*Nature Rev. Neurosci*., 2:229, 2001)

图论和复杂网络理论



Seven Bridges of Königsberg

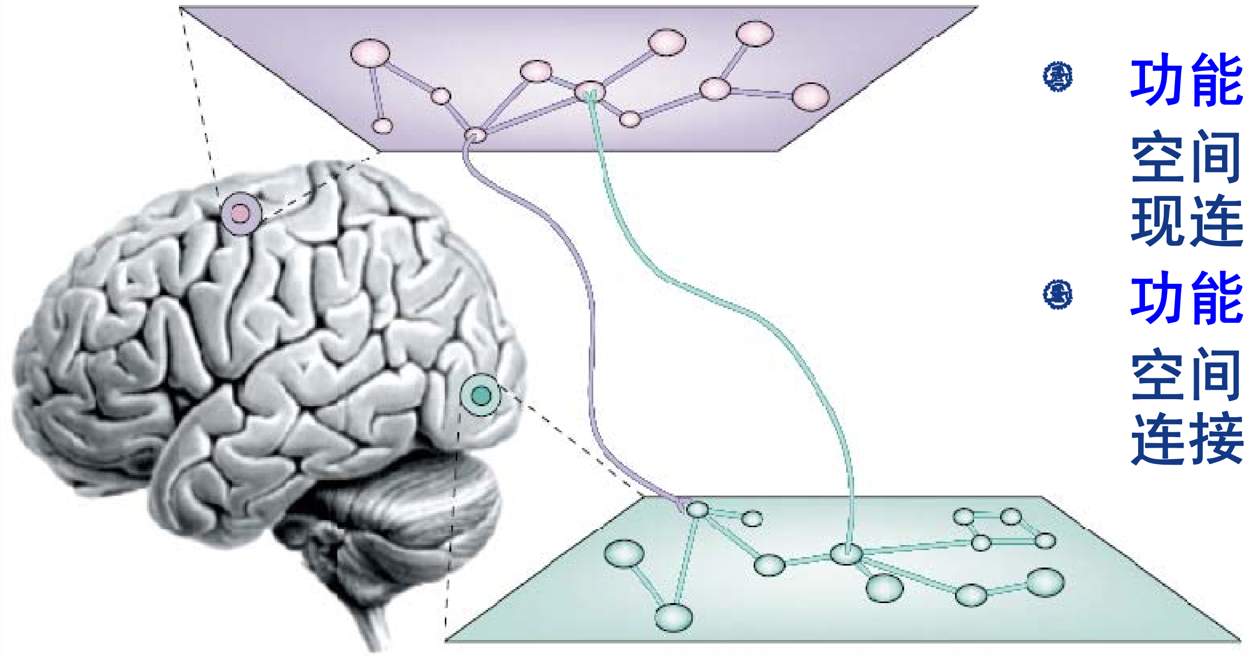


欧拉开创了拓扑学，并
用网络的拓扑学理论证
明了：

要走过哥尼斯堡的七桥
且每桥只通过一次是不
可能的

Leonhard Euler (1907-1783)

大脑神经元的组织原则

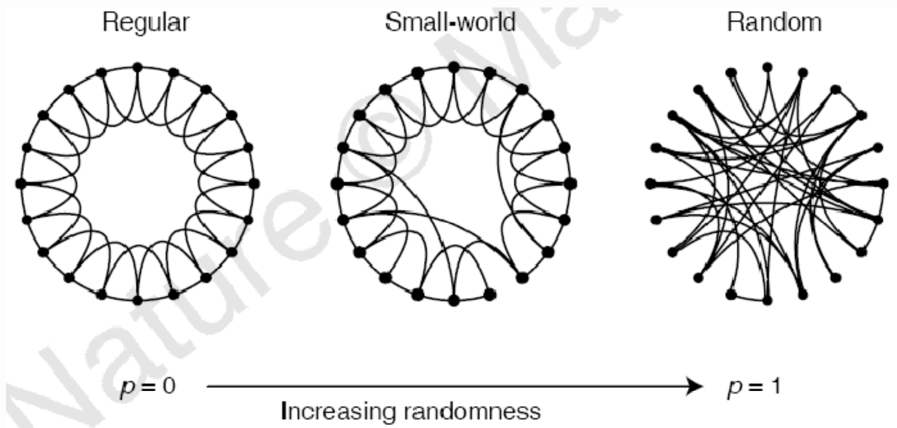


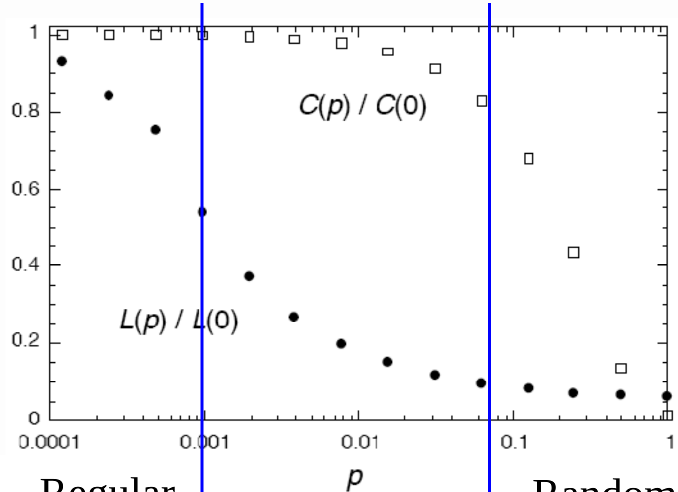
(*Nature Rev. Neurosci*., 2:229, 2001)

- **功能性分化(Segregation):** 空间邻近的神经元之间的出现连接的概率较高
- **功能性整合(Integration) :** 空间远离的神经元之间出现连接的概率较低

大脑的组织原则表明复杂网络理论适用于脑功能分析

小世界网络(Small-world networks)





Regular networks

Random networks

Table 1 Empirical examples of small-world networks

	L_{actual}	L_{random}	C_{actual}	C_{random}
Film actors	3.65	2.99	0.79	0.00027
Power grid	18.7	12.4	0.080	0.005
C. elegans	2.65	2.25	0.28	0.05

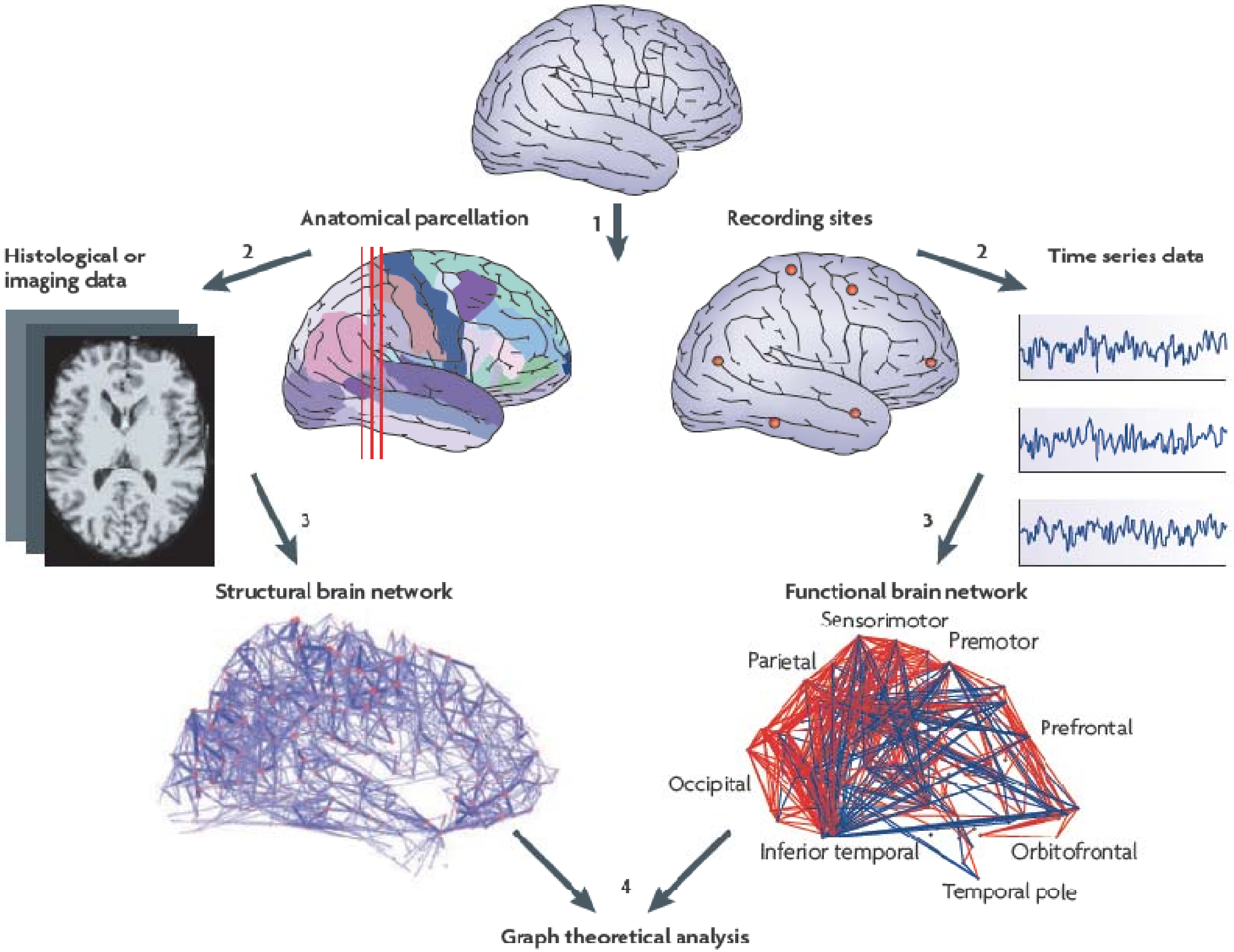
Characteristic path length L and clustering coefficient C for three real networks, compared to random graphs with the same number of vertices (n) and average number of edges per vertex (k). (Actors: $n = 225{,}226$, $k = 61$. Power grid: $n = 4{,}941$, $k = 2.67$. *C. elegans*: $n = 282$, $k = 14$.) The graphs are defined as follows. Two actors are joined by an edge if they have acted in a film together. We restrict attention to the giant connected component[13] of this graph, which includes ~90% of all actors listed in the Internet Movie Database (available at http://us.imdb.com), as of April 1997. For the power grid, vertices represent generators, transformers and substations, and edges represent high-voltage transmission lines between them. For *C. elegans*, an edge joins two neurons if they are connected by either a synapse or a gap junction. We treat all edges as undirected and unweighted, and all vertices as identical, recognizing that these are crude approximations. All three networks show the small-world phenomenon: $L \gtrsim L_{random}$ but $C \gg C_{random}$.

Small-world networks:
big *C*
but small *L*

特征路径长度 $L(p)$
聚类系数 $C(p)$

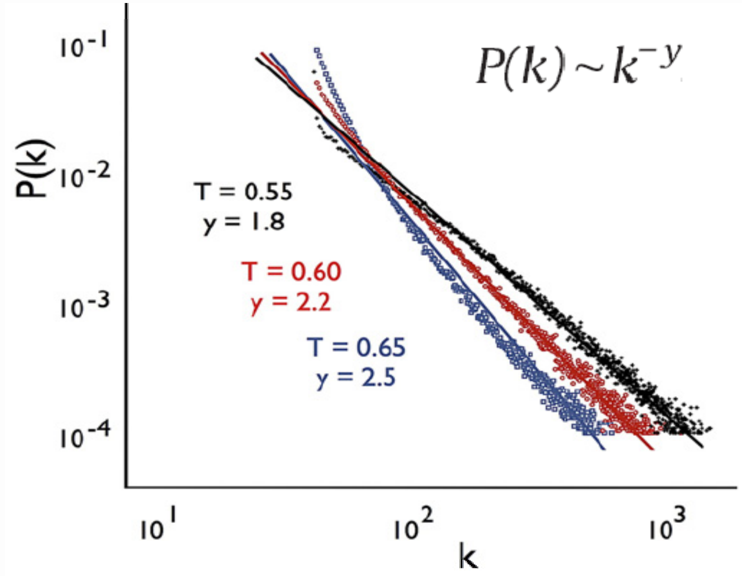
(Watts & Strogatz, *Nature*, 1998)

结构性脑网络和功能性脑网络

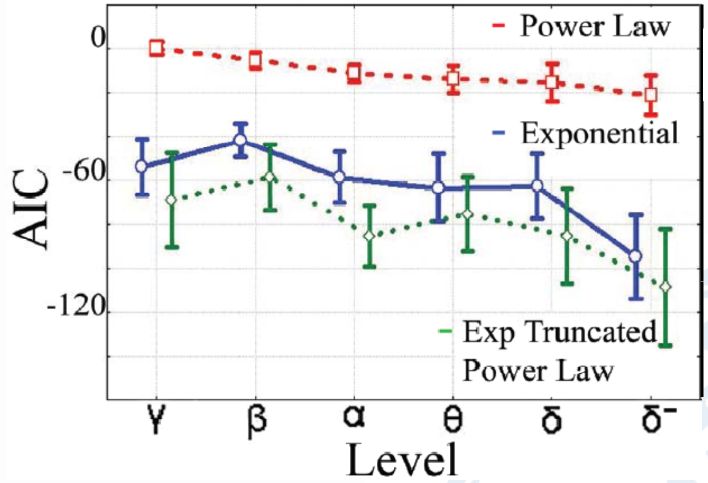


(*Nature Rev. Neurosci*., 10:1, 2009)

脑网络是无标度网络?



Akaike's information criterion (AIC)
for three fits of the degree distribution



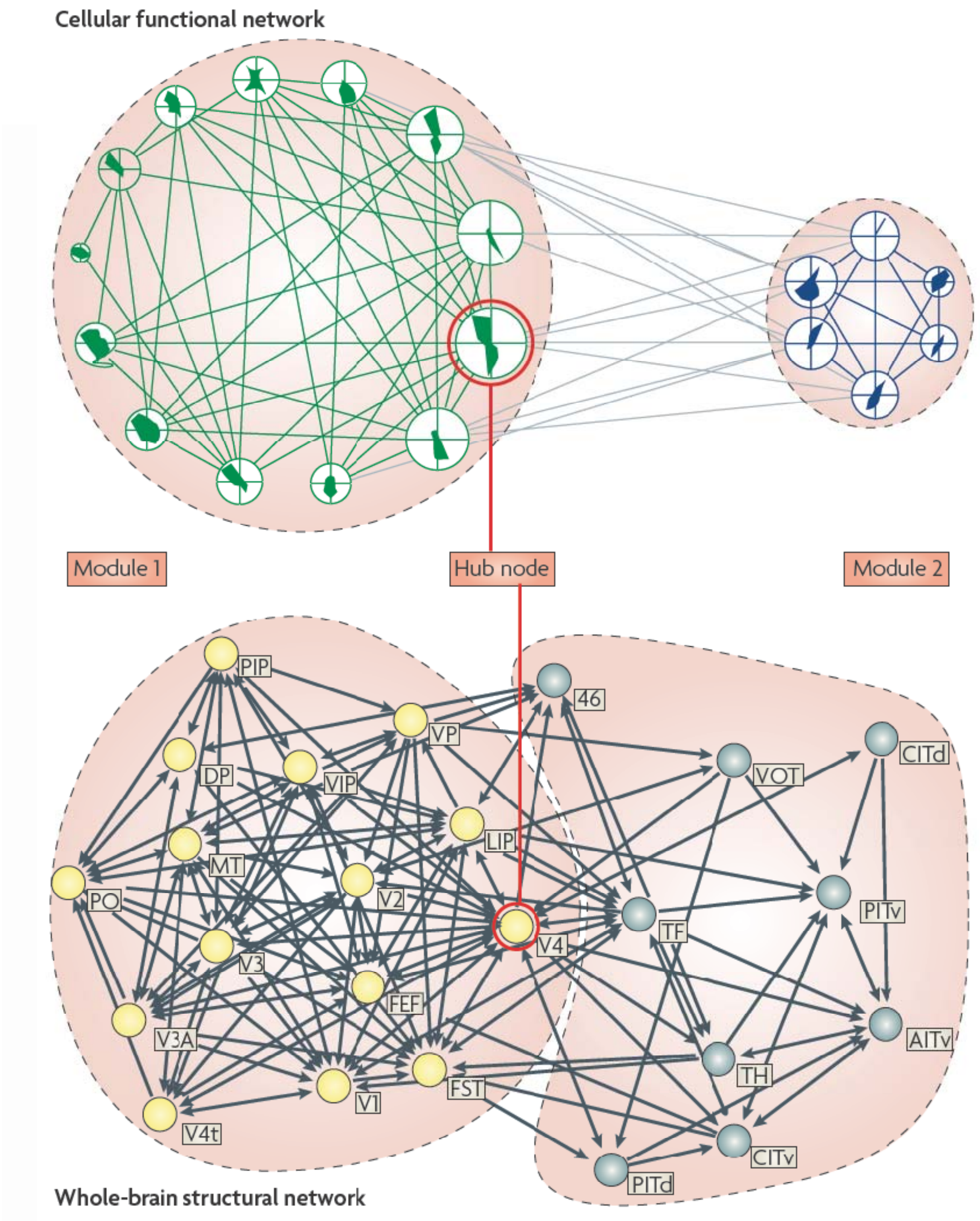
$$P(k) \sim Ak^{\lambda-1}e^{k/k_c}$$

Error bars:
95% confidence
Intervals.

(Heuvel, et al., *NueroImage*, 43:528, 2008)

(Bassett, et al., *PNAS*, 103(51):19518, 2008)

- 有基于fMRI单个体素的高空间分辨率的功能性脑网络研究提示脑网络具有scale-free的组织形式
- 但另有基于fMRI, MEG的功能性脑网络研究，和基于MRI的结构性脑网络研究表明脑网络的度分布服从截断幂律分布 (Truncated power-law)



两种网络表现出相同的特征

- 小世界特征
- Exponentially truncated power-law度分布
- 社团结构(community structure)
- 中心节点(hub node)

- **Top panel: a cellular functional networks constructed from MEA data of cat; each node corresponds approximately to one neuron; circle size corresponds to node degree.**
- **Bottom panel: a whole-brain structural network constructed from histological data on macaque cortex; each node corresponds one brain area.**

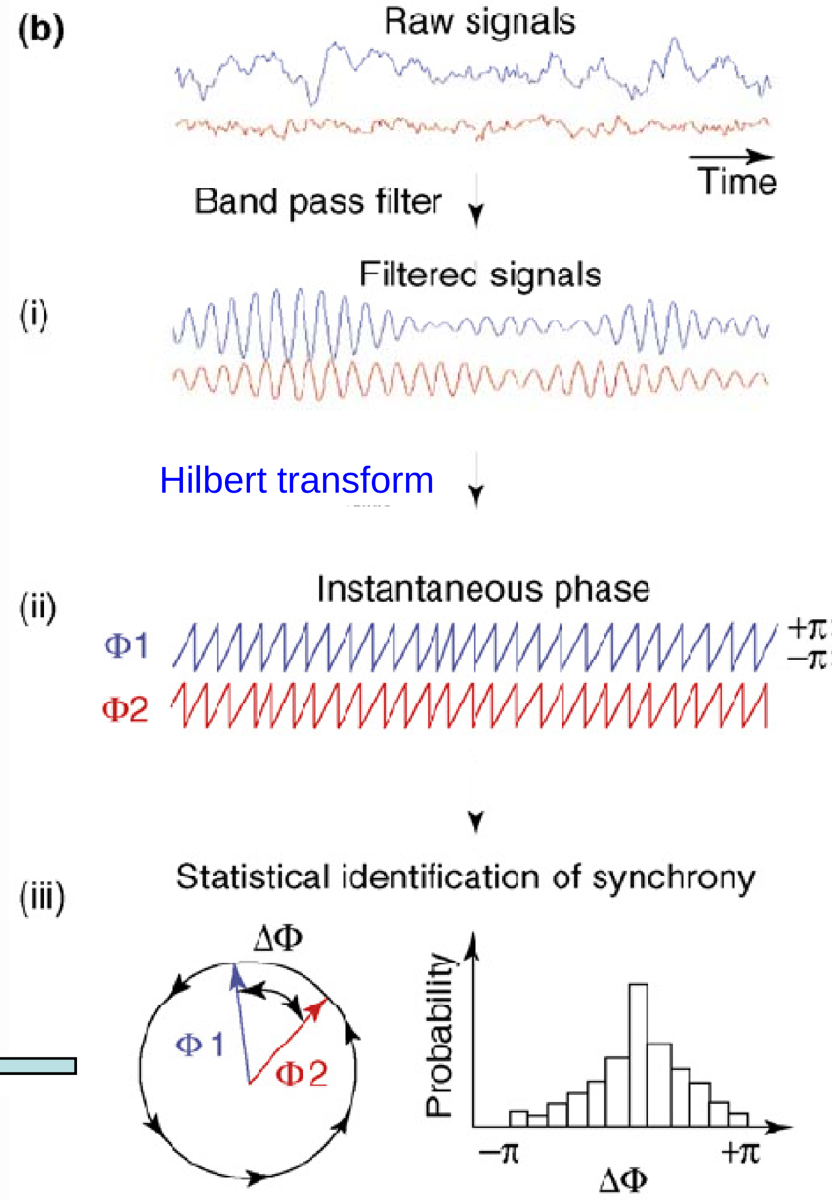
(*Nature Rev. Neurosci*., 10:1, 2009)

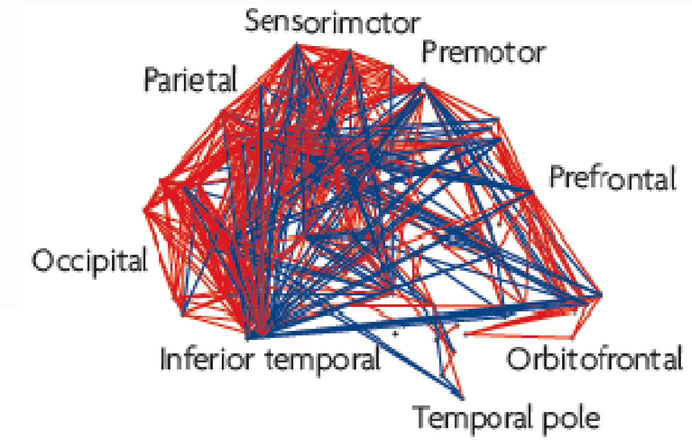
基于EEG的功能性脑网络

1. 定义网络节点

测录EEG数据

2. 基于相位同步分析量化节点之间的关系



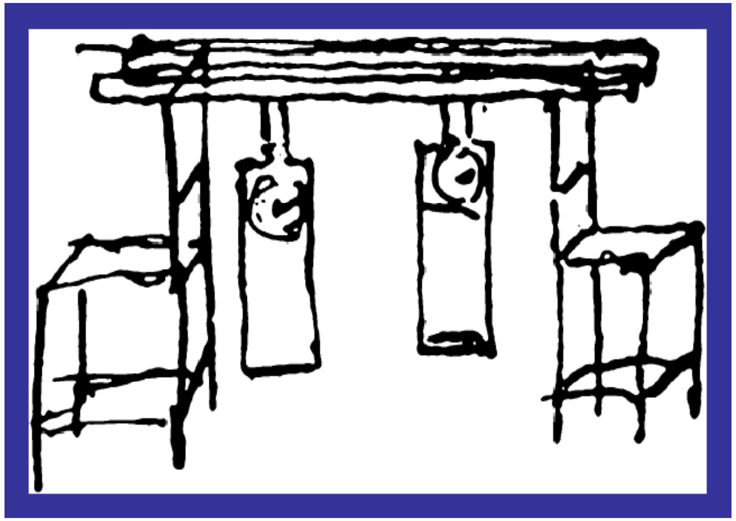


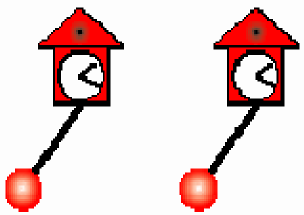
3. 两通道之间的相位同步指数大于设定的阈值，则建立连接边，最终生成网络

4. 分析网络的特征

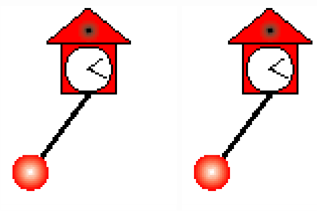
相位同步

荷兰科学家惠更斯在1665年观察到
钟摆同步现象…





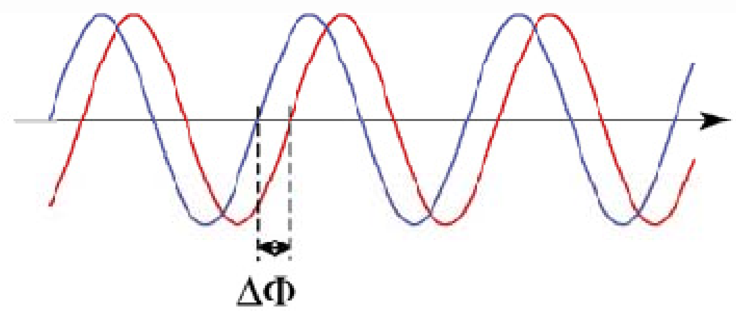
同步



不同步

Christiaan Huygens (1629--1695)

瞬时相位定义研究



$$s^{(h)}(t) = s(t) + j\tilde{s}(t) = A^{(h)}(t)e^{j\phi^{(h)}(t)}$$

Hilbert Transform:

$$\tilde{s}(t) = \frac{1}{\pi}\lim_{\delta \to 0}\left[\int_{-\infty}^{t-\delta}\frac{s(\tau)}{t-\tau}d\tau + \int_{t+\delta}^{+\infty}\frac{s(\tau)}{t-\tau}d\tau\right]$$

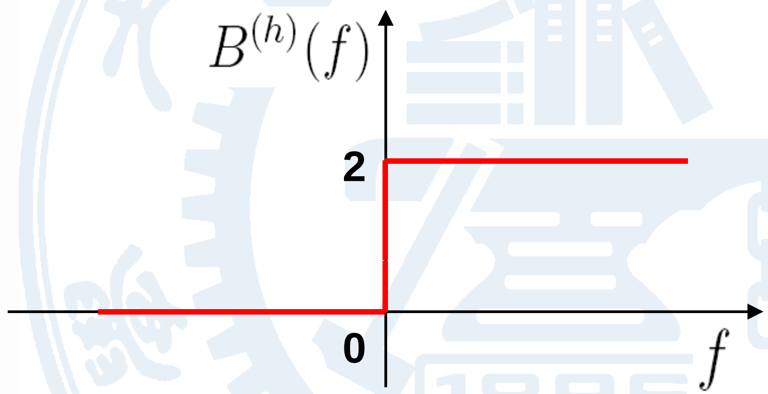
Instantaneous phase： $\phi(t) = \arctan\frac{\tilde{s}(t)}{s(t)}$

$|\phi_1 - \phi_2| <$ const. ⇨ PS

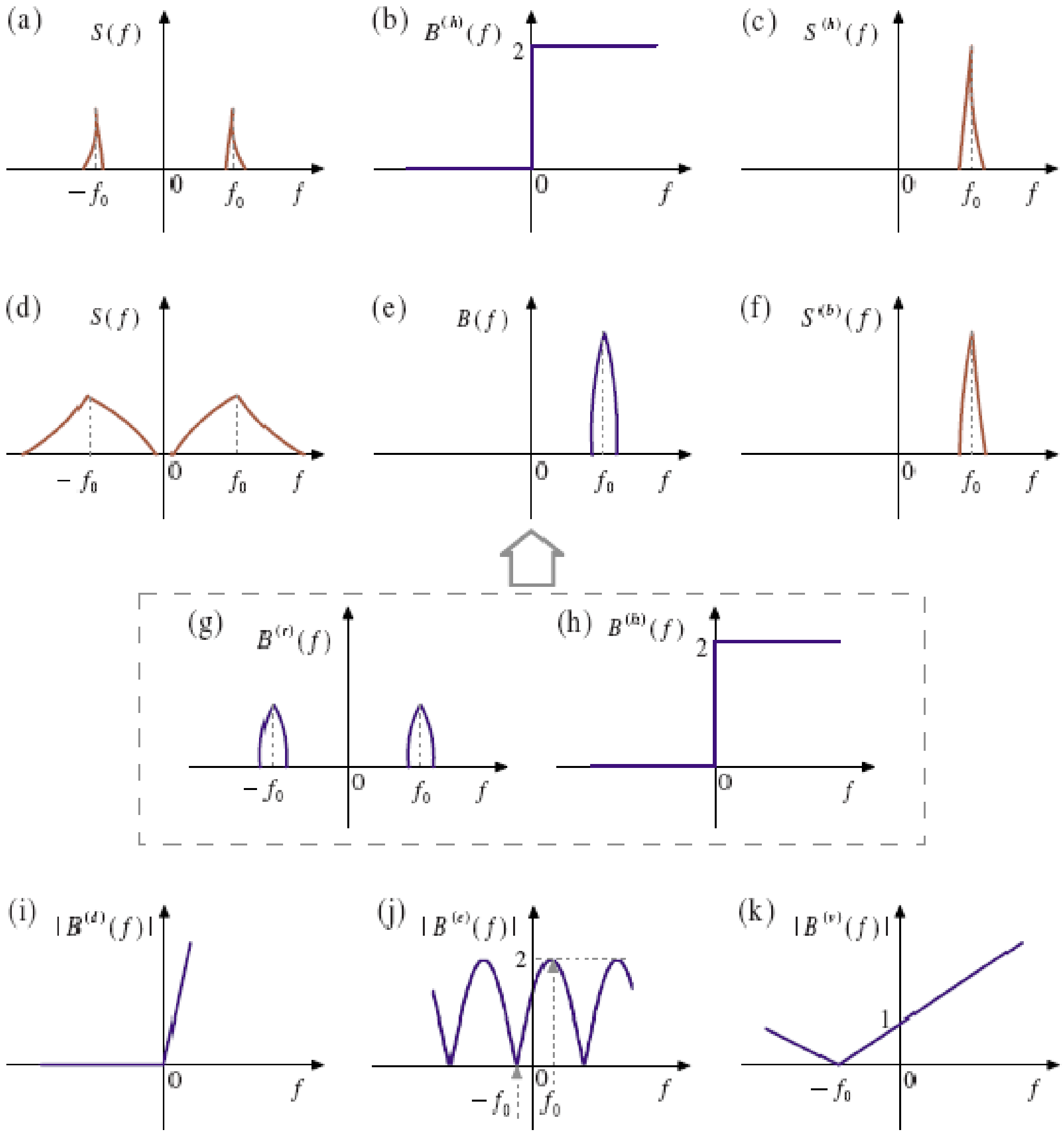
频域形式

$$S^{(h)}(f) = S(f)B^{(h)}(f)$$

$$B^{(h)}(f) = \begin{cases} 2, & \text{if } f > 0 \\ 1, & \text{if } f = 0 \\ 0, & \text{if } f < 0. \end{cases}$$



瞬时相位定义研究



多种瞬时相位定义方法（如基于小波变换）所对应的复信号均可写成原实信号通过某带通滤波器的形式

解析信号： $s^{(b)}(t) = s(t) * b(t)$

滤波器： $b(t) = g(t)e^{j2\pi f_n t}$

$$B(f) = G(f - f_n)$$

瞬时相位： $\phi^{(b)}(t) = \arg[s^{(b)}(t)]$

该定义适用于一般形式的信号

(**Junfeng Sun** and Michael Small, *Physical Review E* 80 (2009):046219)

噪声对相同步检测的影响

$$s(t) = x(t) + w(t)$$

含噪信号 纯净信号 噪声

解析信号
$$\begin{aligned} s^{(b)}(t) &= s(t) * b(t) \\ &= x(t) * b(t) + w(t) * b(t) \\ &= A_x(t) e^{j\phi_x^{(b)}(t)} + w^{(b)}(t), \end{aligned}$$

$$\theta(t) = \hat{\phi}_x^{(b)}(t) - \phi_x^{(b)}(t)$$

相位误差 相位估计值 相位理想值

可证明：在中低等噪声水平下
(信噪比>5dB)，相位误差服从正态分布：

$$p(\theta) = (\sqrt{2\pi}\sigma_\theta)^{-1} e^{-\theta^2/(2\sigma_\theta^2)}$$

$$\sigma_\theta = \sigma_{w^{(b)}} / A_x(t)$$

如相位误差折叠到 $(0 \ \ 2\pi]$
则其满足折叠高斯分布：

$$p(\Theta) = \frac{1}{\sqrt{2\pi}\sigma_\theta} \sum_{k=-\infty}^{\infty} e^{-(\Theta + 2k\pi)^2/(2\sigma_\theta^2)}$$

$$\Theta = \theta \ (mod \ 2\pi)$$

(**Junfeng Sun** and Michael Small, *Physical Review E* 80 (2009):046219)

噪声对相同步检测的影响

采用平均相位相干性(mean phase coherence, MPC)作为相同步指数

$$\hat{\rho} = \left\{ \left[\frac{1}{L} \sum_{n=0}^{L-1} \cos \hat{\varphi}(n) \right]^2 + \left[\frac{1}{L} \sum_{n=0}^{L-1} \sin \hat{\varphi}(n) \right]^2 \right\}^{1/2}$$

其中 $\hat{\varphi} = \hat{\phi}_{x_1}^{(b)} - \hat{\phi}_{x_2}^{(b)}$ 是两耦合系统之间的瞬时相位差

如假设混合正态分布可用某一正态分布近似，则可证明相同步指数与噪声水平之间满足以下关系：

$$\hat{\rho} = e^{-(\sigma_{\theta_1}^2 + \sigma_{\theta_2}^2)/2} \rho$$

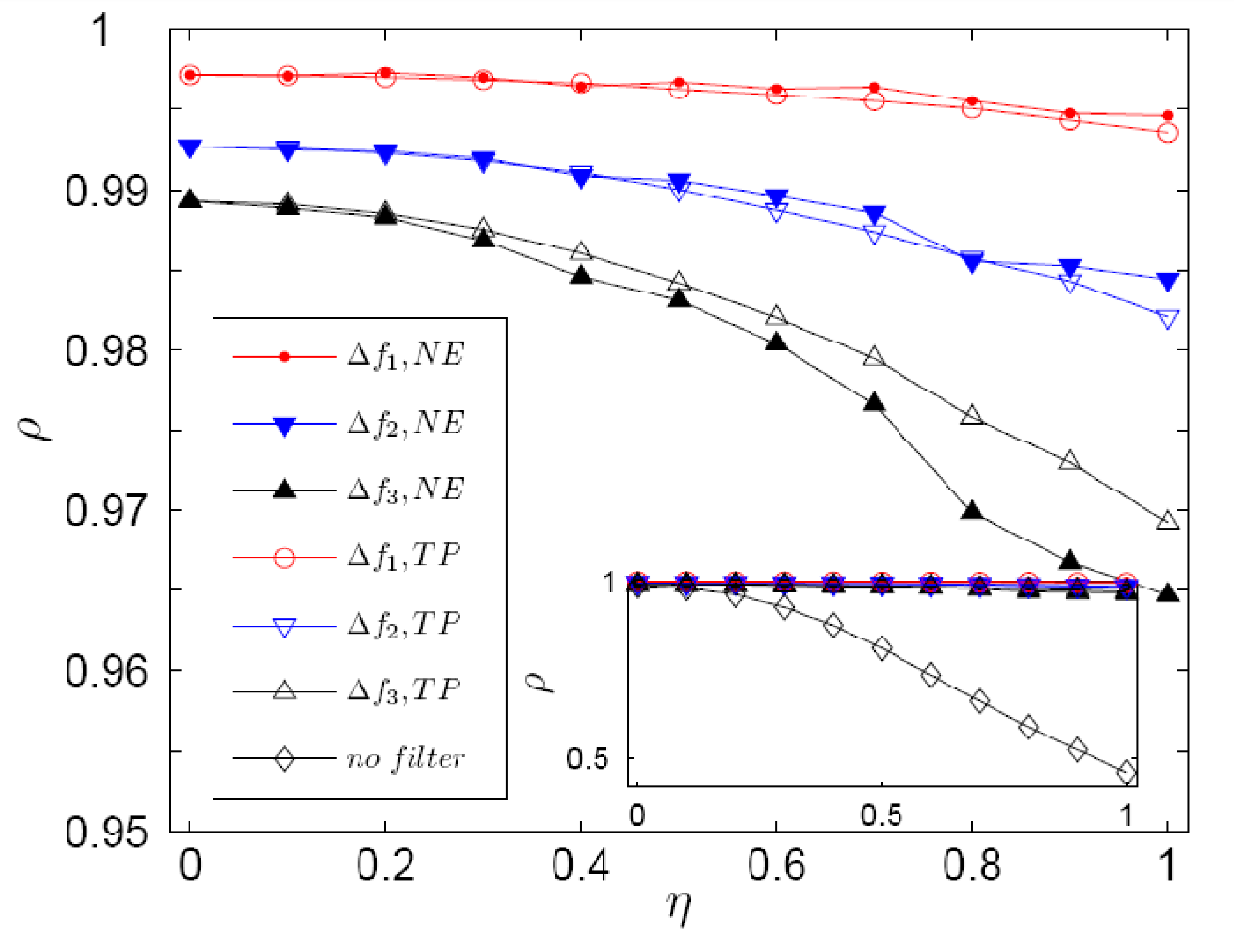
由含噪信号估计出的同步指数

噪声导致的影响

由纯净信号估计出的同步指数

(**Junfeng Sun** and Michael Small, *Physical Review E* 80 (2009):046219)

噪声对相同步检测的影响



耦合Rössler系统
处于相同步状态

耦合强度：

$$\xi = 0.035$$

NE – 数值估计
TP – 理论预测

(**Junfeng Sun** and Michael Small, *Physical Review E* 80 (2009):046219)

中风病例概况表

Table 1

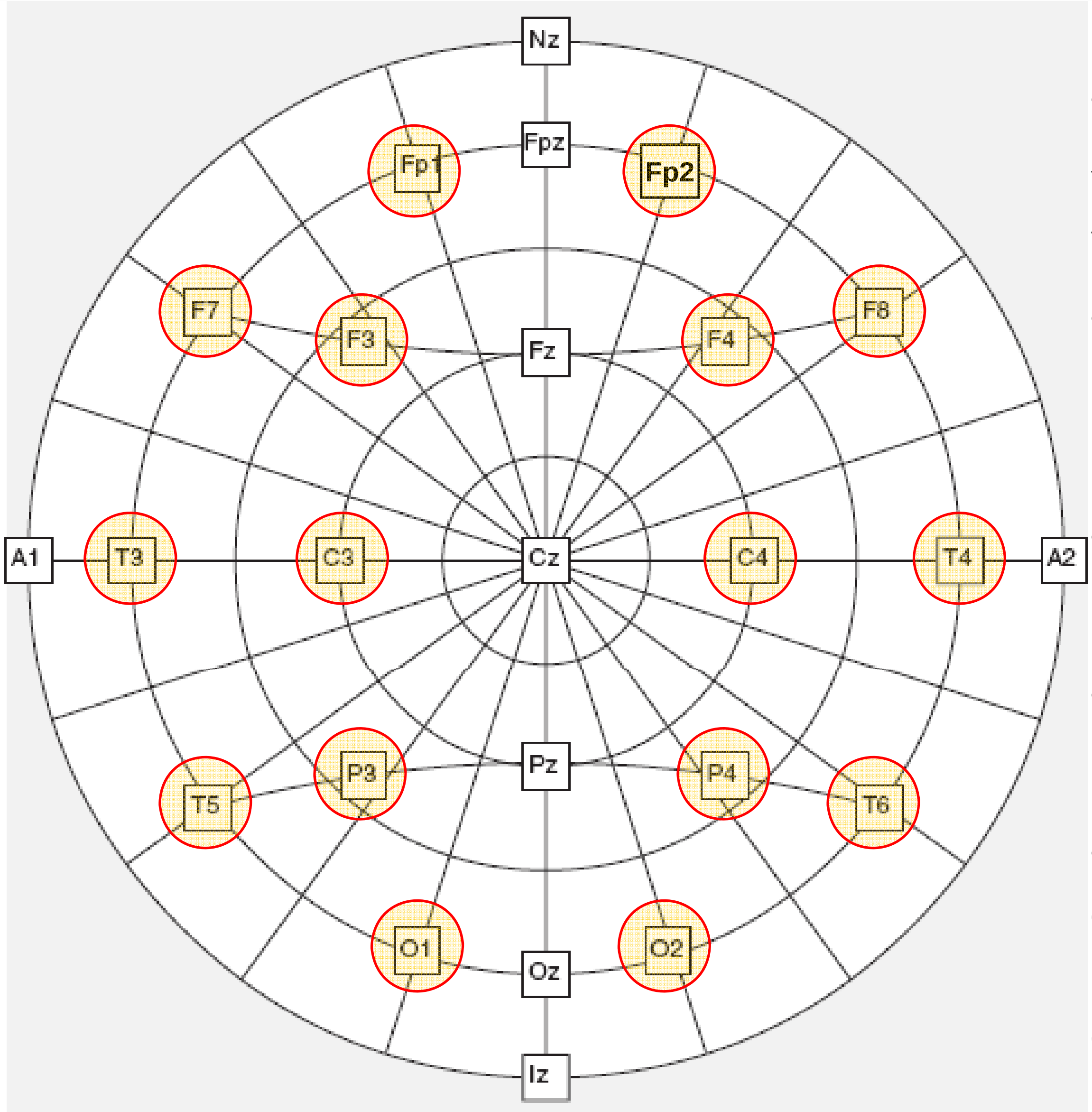
Neurological and clinical profiles in terms of lesion site, gender, age, and clinical neurological scores (NIHSS).

Lesion site	Gender (male/female)	Age (years)	NIHSS_1	NIHSS_2
Left-hemispheric stroke	8/9	73.7 ± 10.1	14.8 ± 4.4	7.8 ± 2.9*
Right-hemispheric stroke	8/4	71.1 ± 9.2	13.7 ± 5.0	6.7 ± 2.4*
Bilateral stroke	7/6	67.5 ± 12.8	11.7 ± 3.5	5.2 ± 2.2**

Patients are grouped according to lesion sites (left hemispheric ischemic stroke, right hemispheric ischemic stroke, and bilateral stroke patients). NIHSS_1 was recorded within seven days after the onset of stroke, while NIHSS_2 was recorded two months after the injury. Data are listed as mean ± standard deviation. NIHSS was significantly lower two months after the injury compared with those within seven days after the onset of stroke ($^{*}p < 0.01$, $^{**}p < 0.001$).

(Wenqing Wu, **Junfeng Sun**, *et. al.*, *Clinical Neurophysiology*, *in press*)

受试者EEG数据采集



- 30 min EEG recording with subjects seated in resting state with eyes closed
- EEG data at 16 scalp loci; 10-20 system; reference to linked earlobe
- Sunray LQWY-N systems, 12-bits A/D, 100 Hz
- Filtered to alpha frequency band (8-13 Hz)
- Phase synchrony of pairs of channels calculated from 15 segments (each 10 s) for each subject

(S. J. Luck, *An Introduction to the Event-Related Potential Technique*, The MIT Press, 2005)

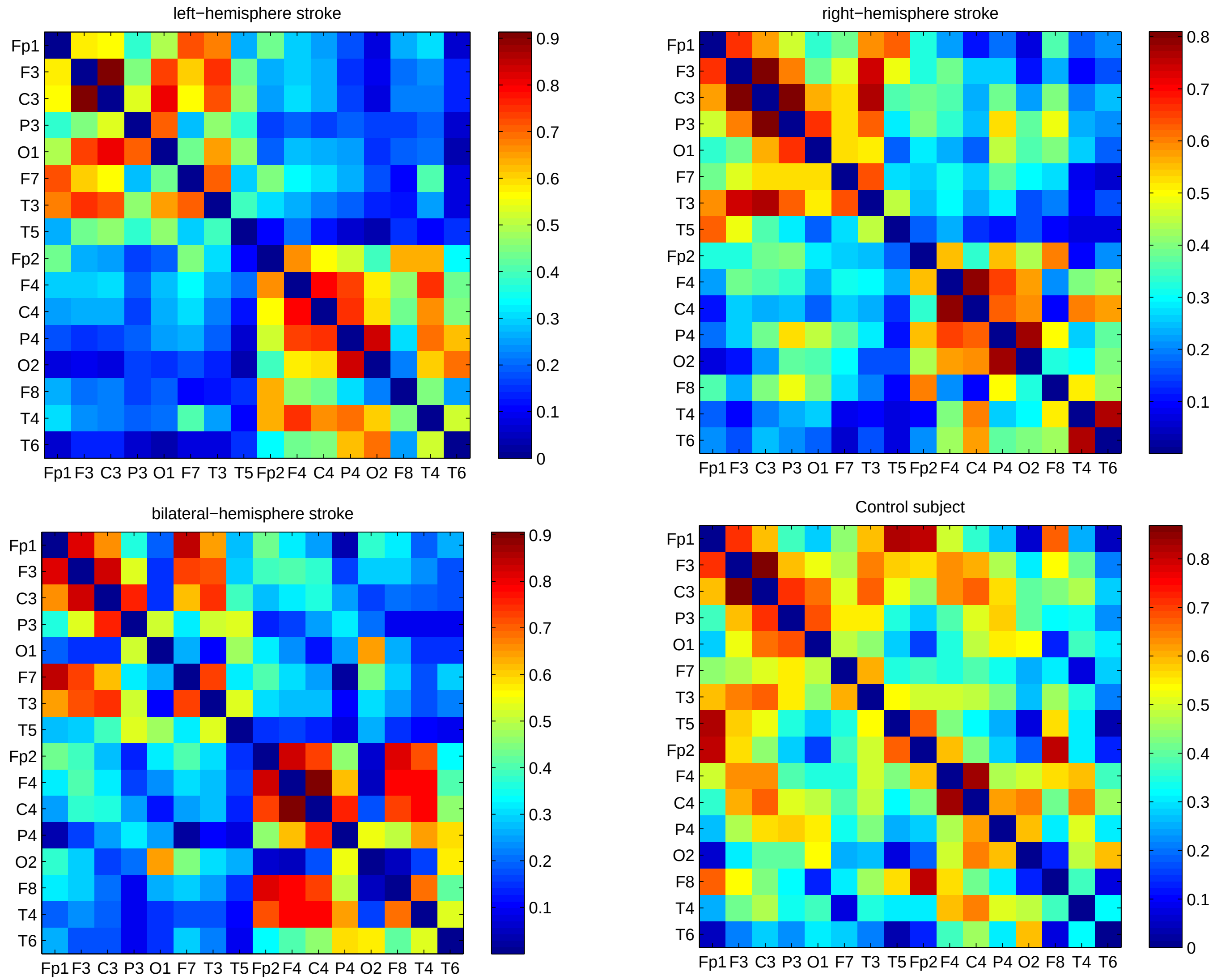
节点间相同步指数强度示例

左脑半球
中风病例

右脑半球
中风病例

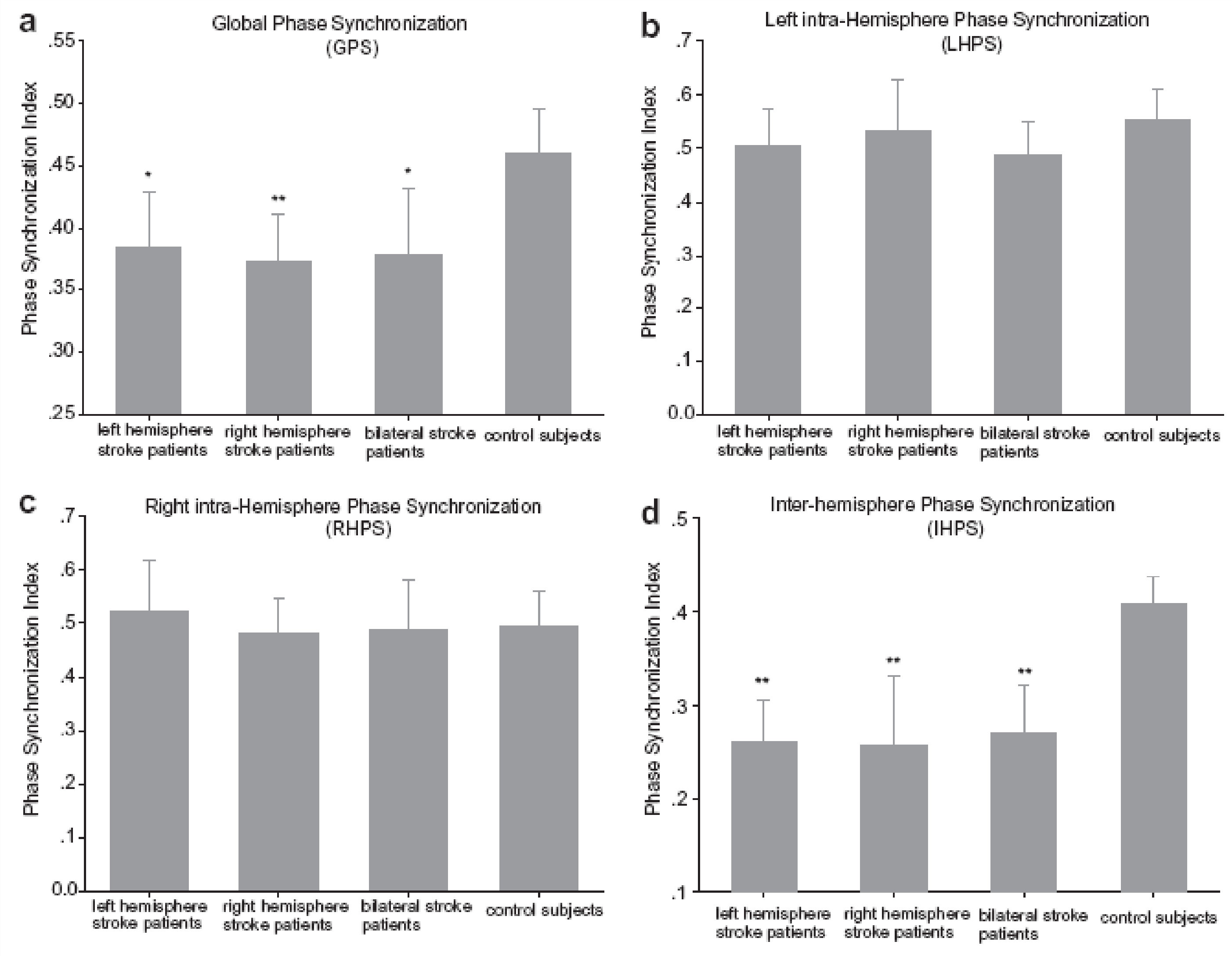
两侧脑半球
均中风病例

健康
对照者



(Wenqing Wu, **Junfeng Sun**, *et. al.*, *Clinical Neurophysiology, in press*)

脑缺血病例的节点间同步指数统计



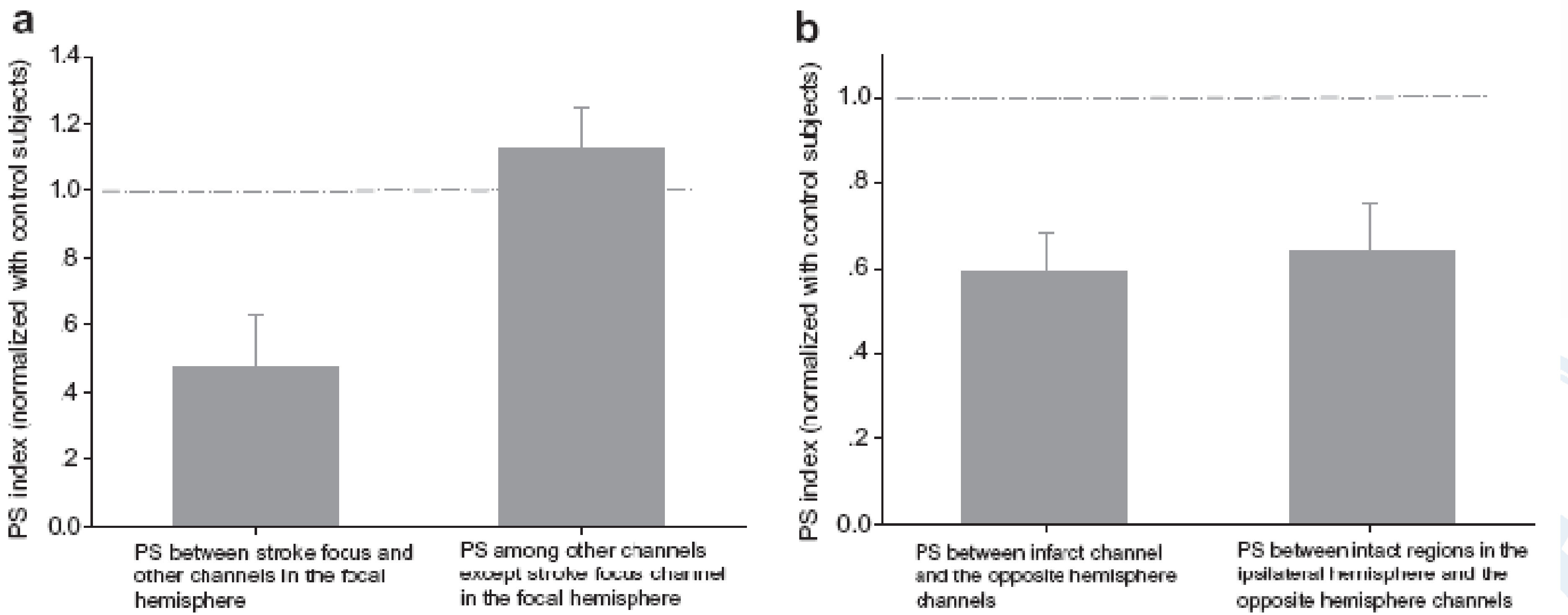
$^{*}p < 0.01$

$^{**}p < 0.001$

Within 7 days

(Wenqing Wu, **Junfeng Sun**, *et. al.*, *Clinical Neurophysiology*, *in press*)

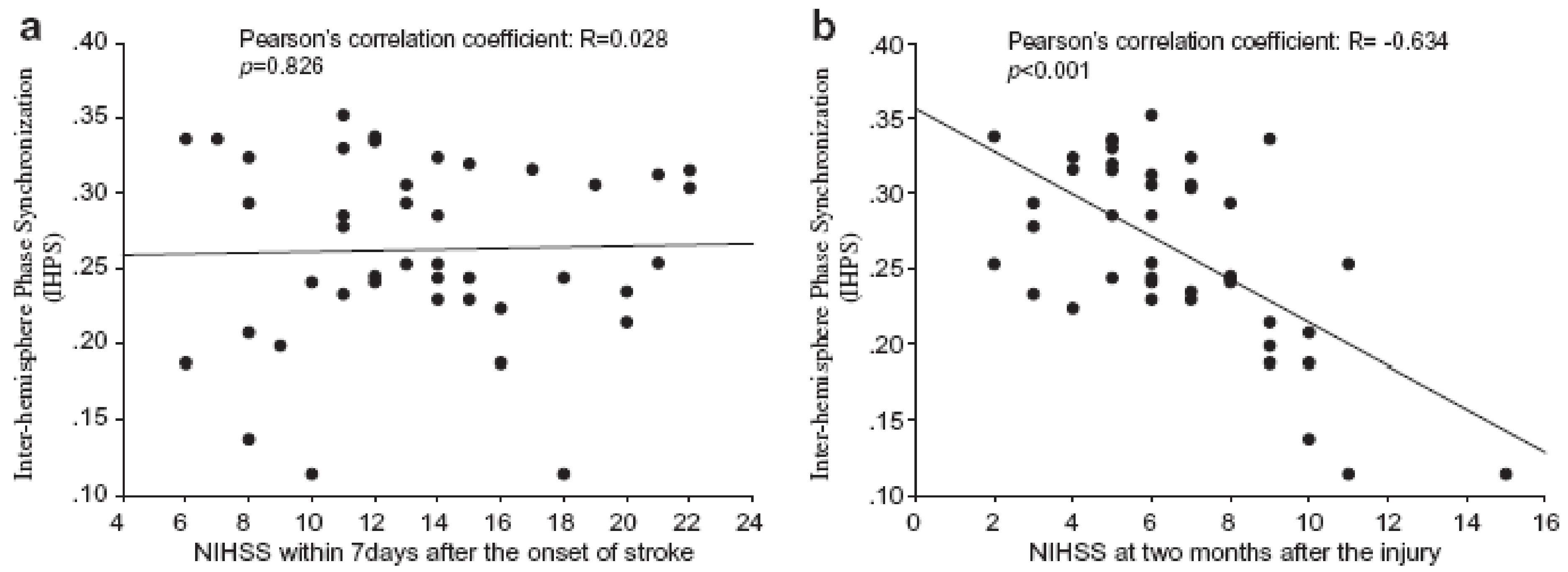
单侧脑缺血病例的节点间同步指数统计



Dashed line indicates normalized valuse for the control subjects

(Wenqing Wu, **Junfeng Sun**, *et. al*., *Clinical Neurophysiology*, *in press*)

脑半球间相位同步指数与NIHSS的关系

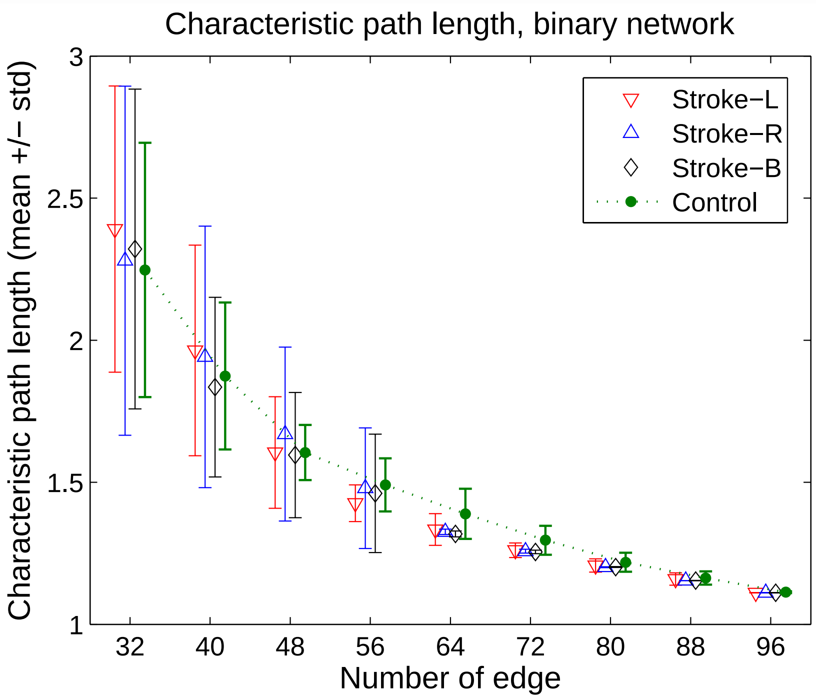


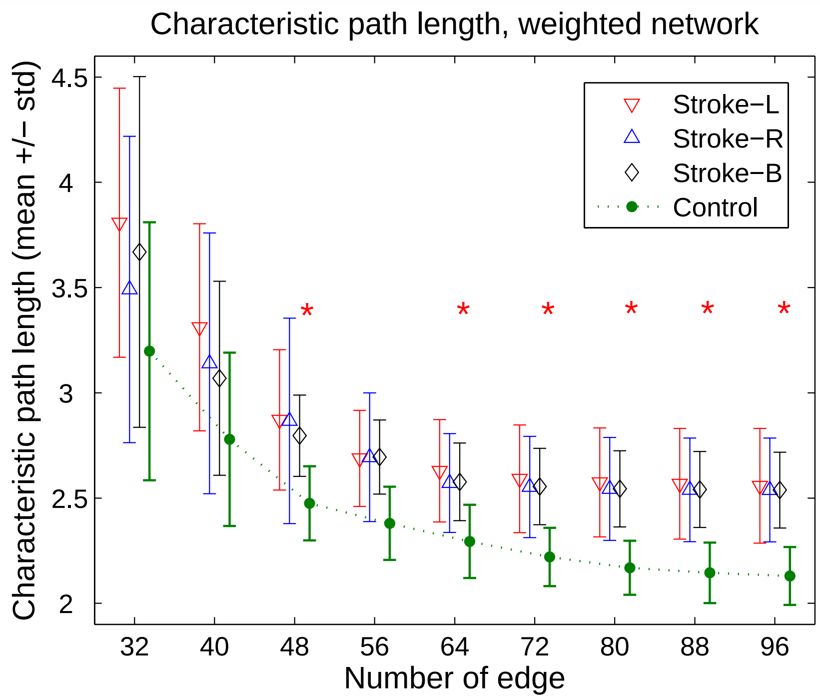
NIHSS：National Institute of Health Stroke Scale

脑缺血后早期脑半球间的EEG相位同步水平越高，
意味着患者后期能康复得越好

(Wenqing Wu, **Junfeng Sun**, *et. al.*, *Clinical Neurophysiology*, *in press*)

特征路径长度：中风病例 VS. 对照者



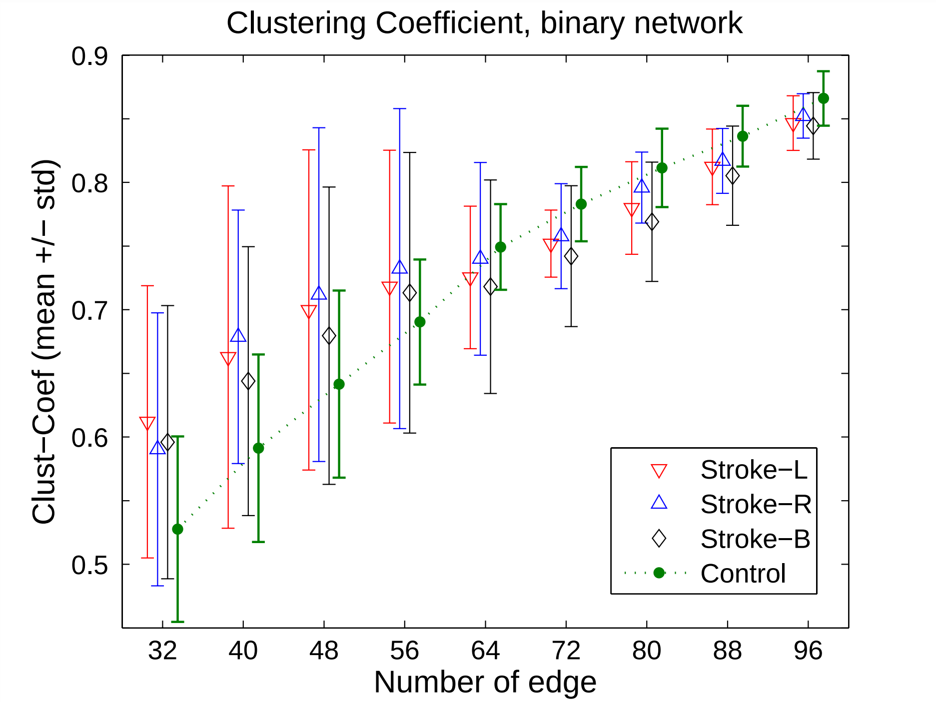


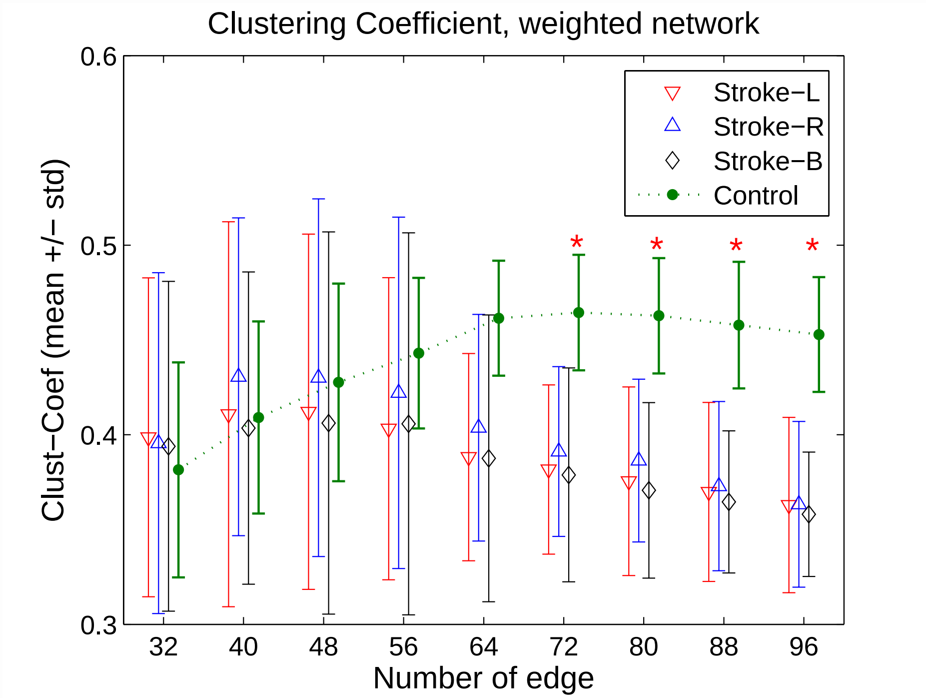
特征路径长度定义：

$$L = \frac{N(N-1)}{\sum_{i=1}^{N}\sum_{j\neq i}^{N} 1/l_{ij}},\ l_{ij} = \min_{i\Leftrightarrow j}(\mathrm{sum}(d_{ij})),\ d_{ij} = 1/\rho_{ij}$$

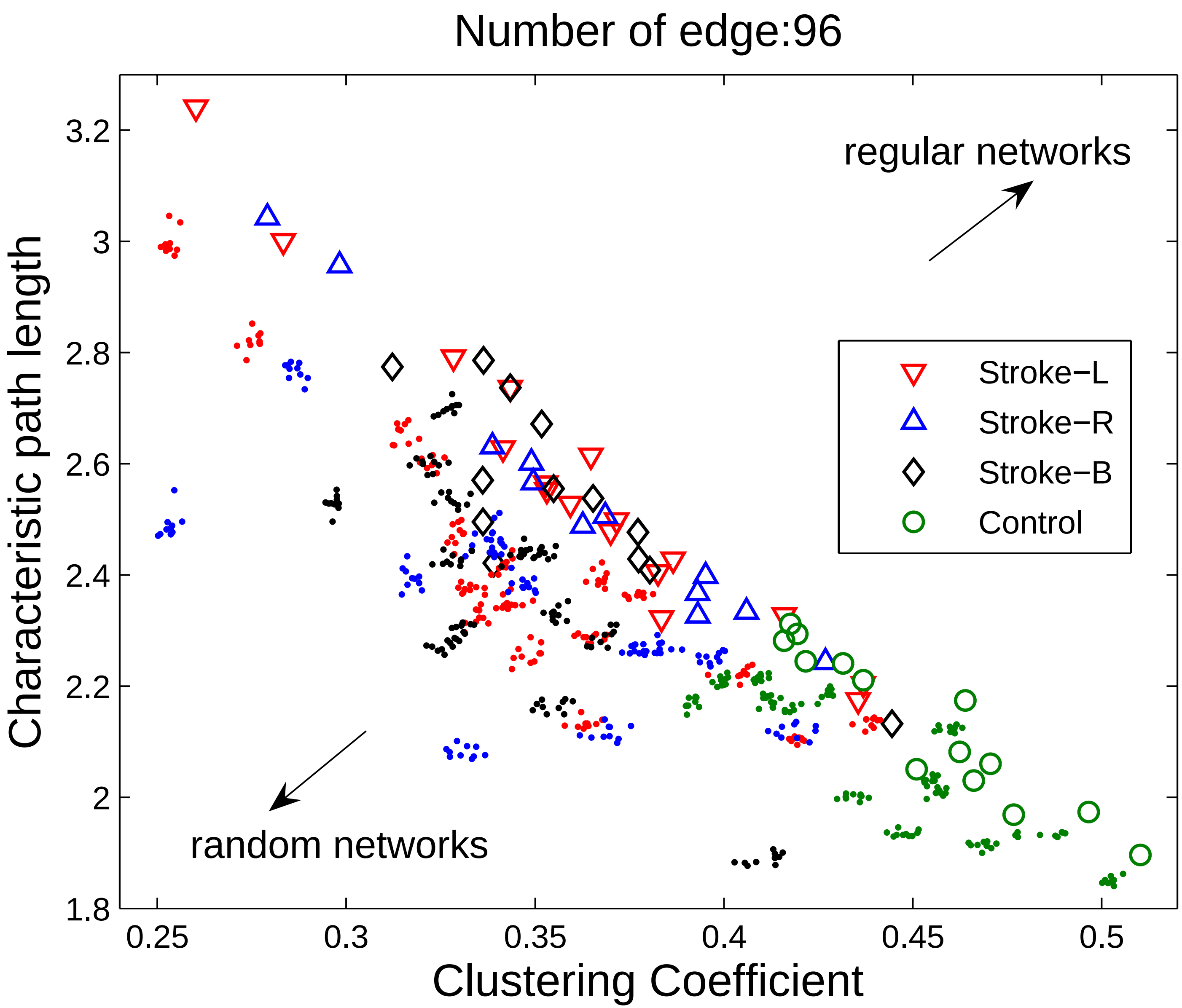
(Newman MEJ, *SIAM Rev*., 2003, 45: 167-256)

聚类系数：中风病例 VS. 对照者

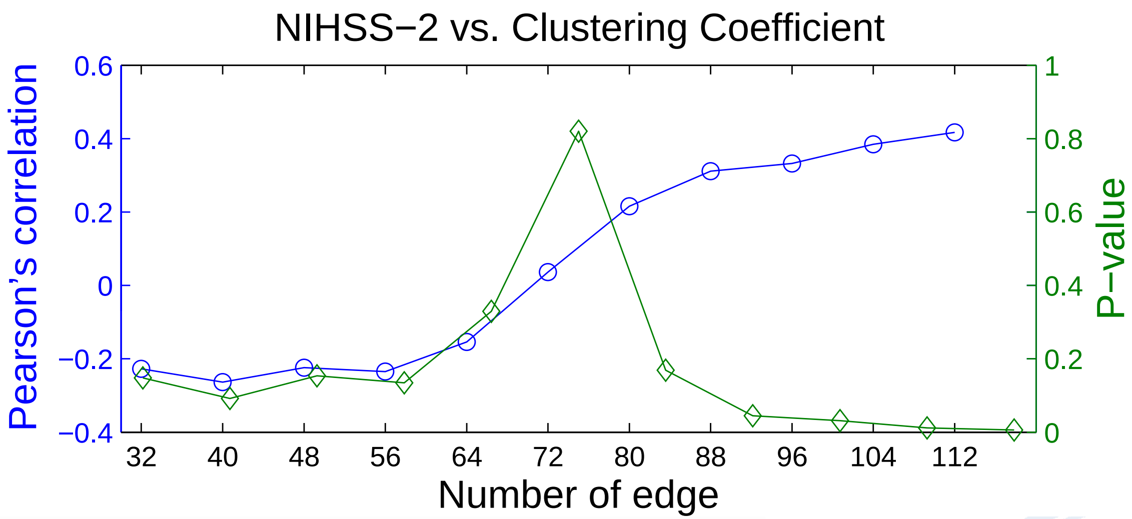


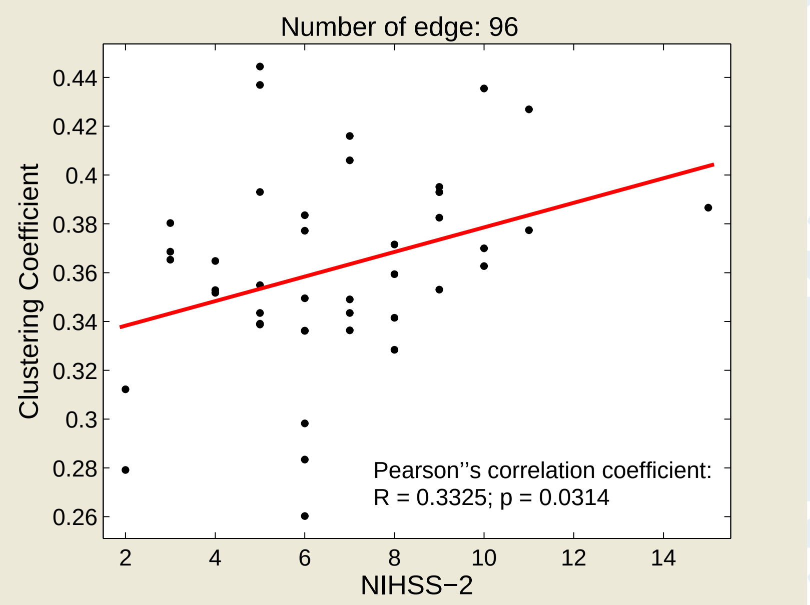


聚类系数 VS. 特征路径长度

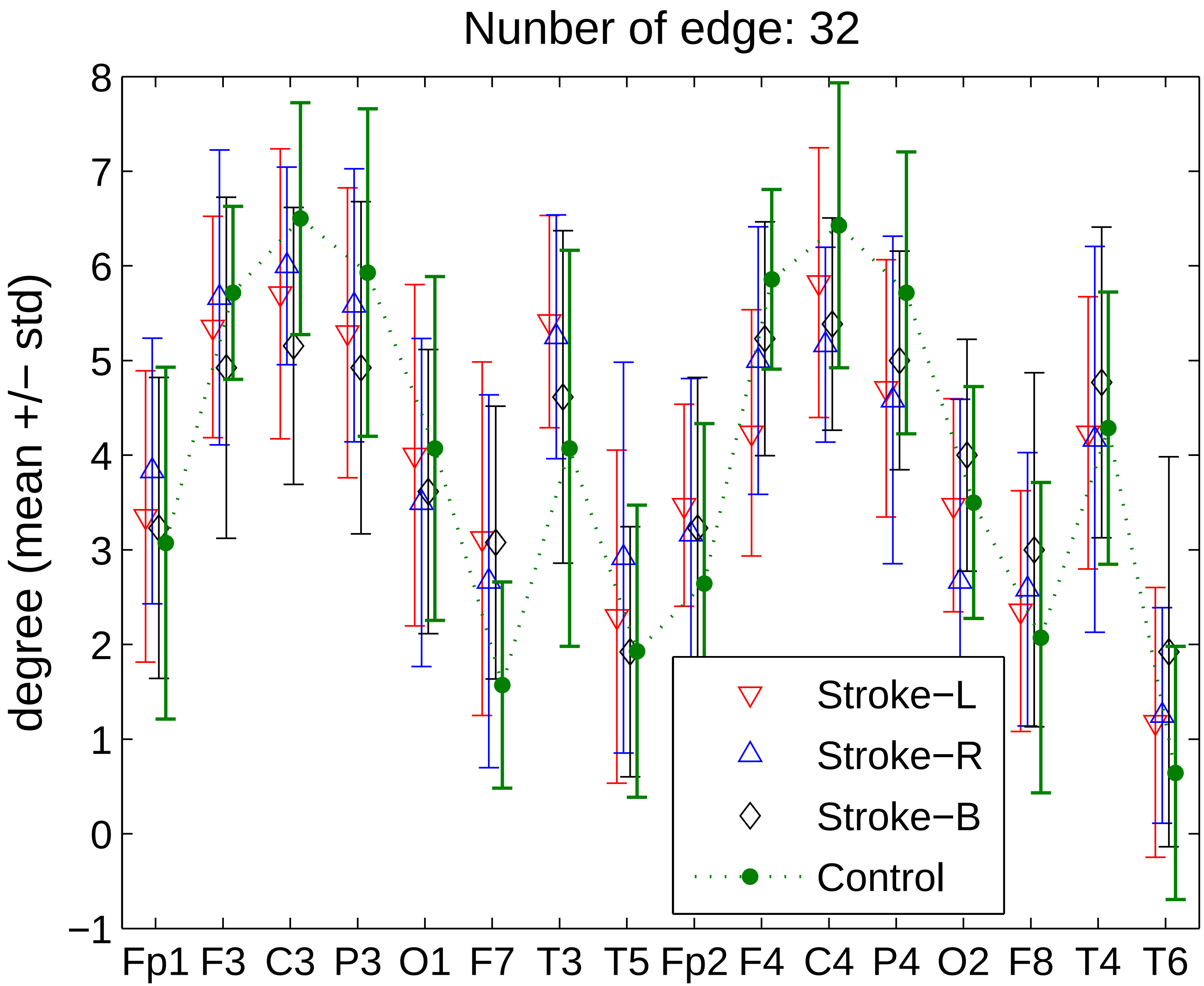


NIHSS vs. 网络特征参数



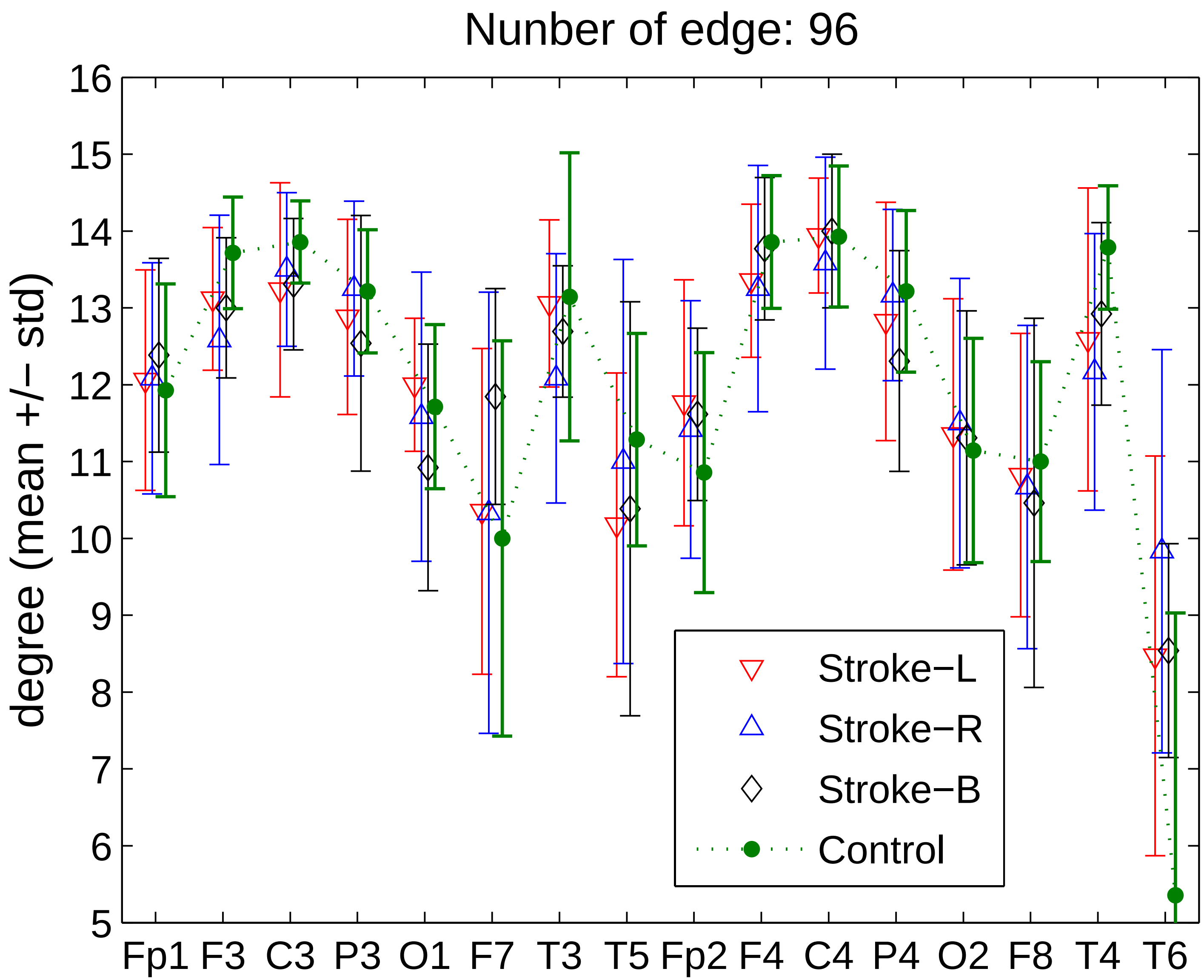


度分布



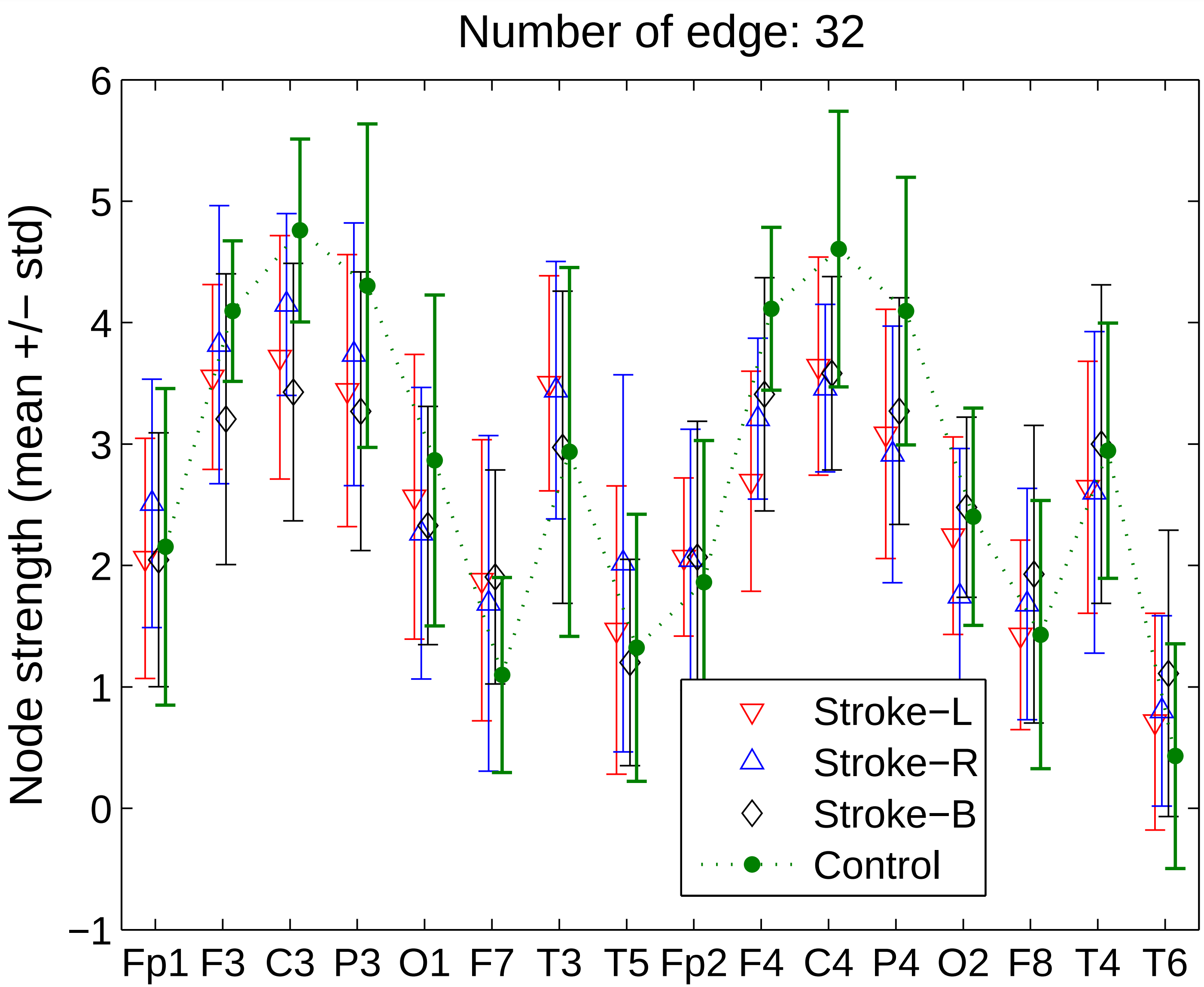
Nunber of edge: 32
degree (mean +/− std)
8
7
6
5
4
3
2
1
0
−1
Fp1 F3 C3 P3 O1 F7 T3 T5 Fp2 F4 C4 P4 O2 F8 T4 T6
Stroke−L
Stroke−R
Stroke−B
Control

度分布



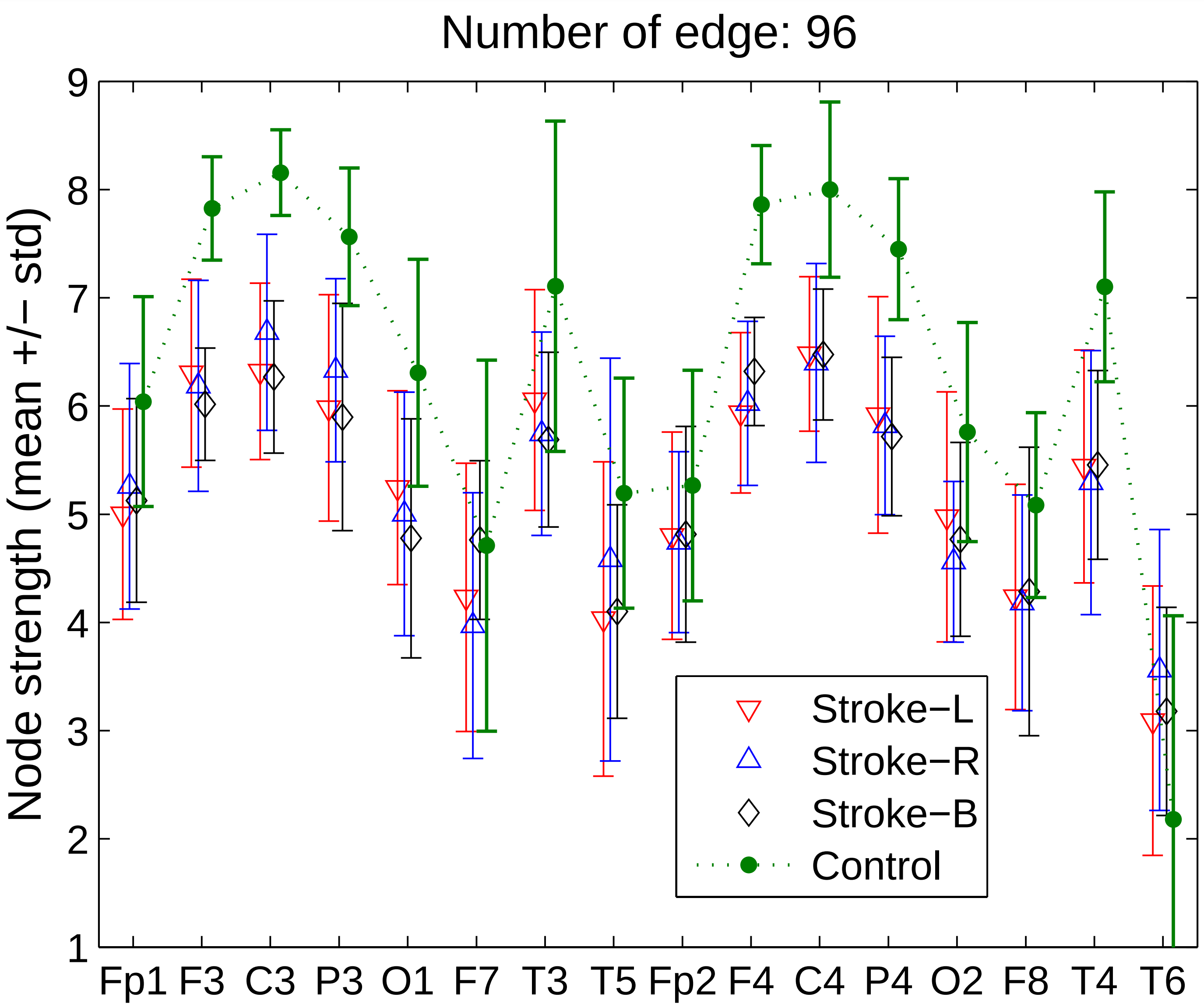
Nunber of edge: 96
degree (mean +/− std)
16
15
14
13
12
11
10
9
8
7
6
5
Fp1 F3 C3 P3 O1 F7 T3 T5 Fp2 F4 C4 P4 O2 F8 T4 T6
Stroke−L
Stroke−R
Stroke−B
Control

节点强度

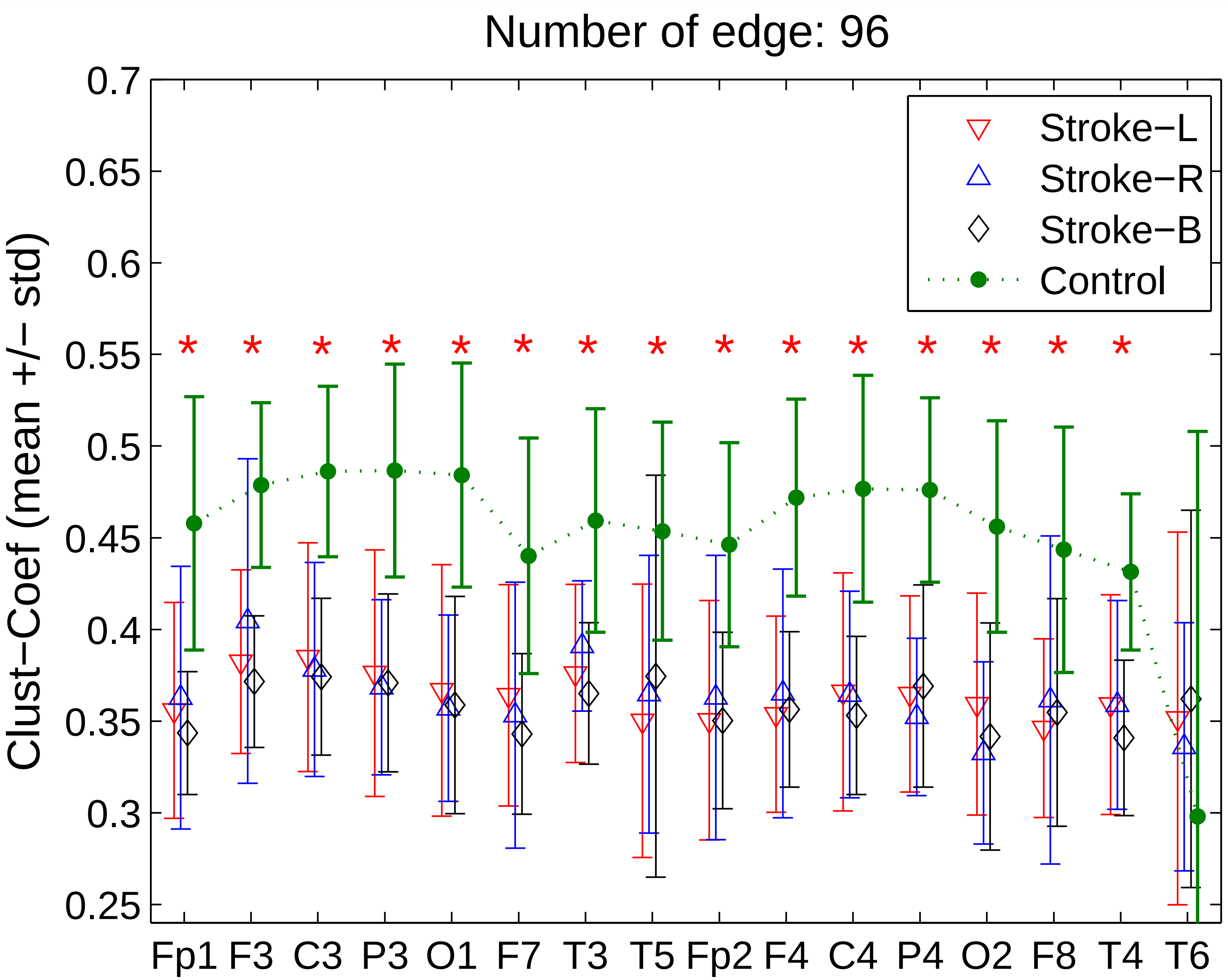


Number of edge: 32
Node strength (mean +/− std)
6
5
4
3
2
1
0
−1
Fp1 F3 C3 P3 O1 F7 T3 T5 Fp2 F4 C4 P4 O2 F8 T4 T6
Stroke−L
Stroke−R
Stroke−B
Control

节点强度


Number of edge: 96
Node strength (mean +/− std)
9
8
7
6
5
4
3
2
1
Fp1 F3 C3 P3 O1 F7 T3 T5 Fp2 F4 C4 P4 O2 F8 T4 T6
Stroke−L
Stroke−R
Stroke−B
Control

各节点的聚类系数



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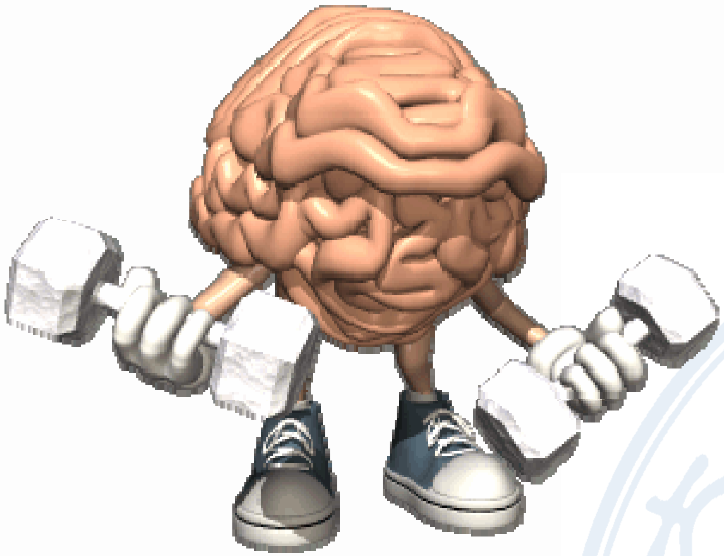
Q & A



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