Supplemental Materials

Configurations of 512-channel tetrode system

To construct tetrodes, four wires were twisted together using a manual turning device and soldered with a low-intensity heat source. The impedances of the tetrodes were measured with an electrode impedance tester to detect any faulty connections, and our tetrodes were typically between 0.7 and 1 MΩ. The insulation was removed by moving the tips of the free ends of the tetrodes over an open flame. A tetrode length of 7 cm or 9 cm was optimal, shown as Fig. 1(a), so that each of the 13 sites could accurately be reached. The tetrodes were then placed into appropriate polyimide tubes. Importantly, the recording ends of the tetrodes were cut differentially so that multiple recording sites, located at different depths, could be reached with the same module. This ensures that only tetrodes, but not the surrounding polyimide tubes, were inserted into the brain tissue, thereby minimizing tissue damage. Two grounding wires were used for each module: one is to be attached to the skull and the other to the copper-mesh cage wrapped around the finished headstage after surgery.

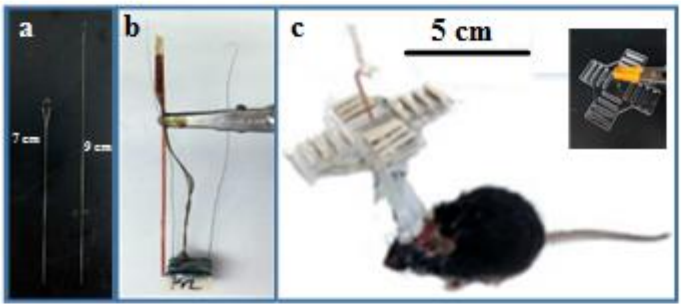

Fig. 1 (a) Two different lengths of tetrode wires. (b) An assembled PrL/ Cg1/Cg2 module consisting of three 32-connector pins with 96-channel arrays. The copper bar was used for temporally holding the assembled polyimide tubes and connector pins during the construction of the module and surgery. The tips of tetrodes protruding from the polyimide tubes are inserted into the brain. (c) A mouse with a 512-channel headstage.

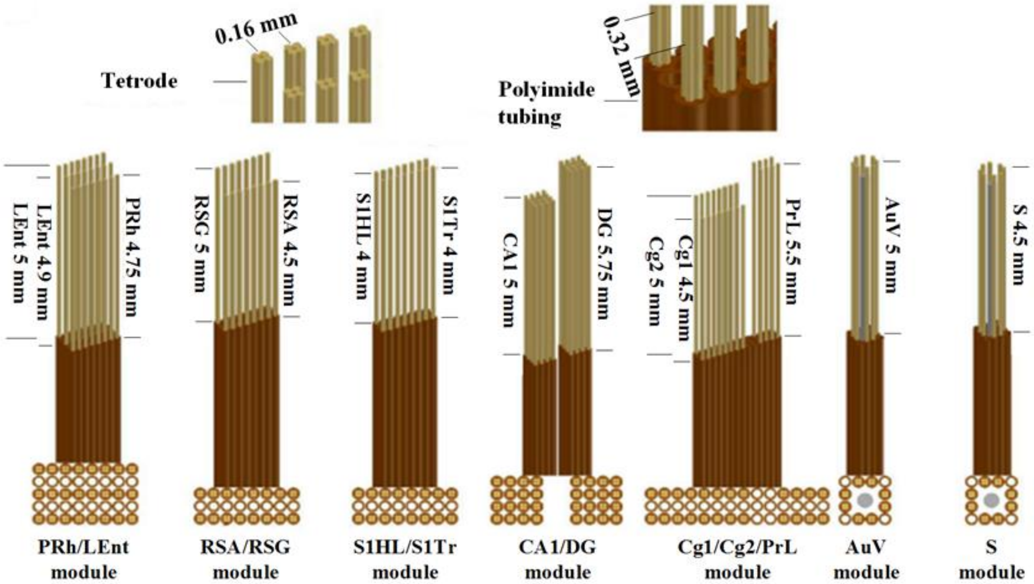

Fig. 2 Specifications of various tetrode arrays used for constructing seven different brain region modules.

Since some of these thirteen brain regions are located next to each other, as well as to minimize the number of holes on the mouse's skull, two or three bundles of nearby regions were grouped in a single module of tetrode arrays. Therefore, the 512-channel tetrode system was constructed with seven separate modules: CA1&DG module, S1Tr&S1HL module, RSG&RSA module, S module, PRh&LEnt module, AuV module, and Cg1&Cg2&PrL module. Based on the unique anatomical shape of each brain structure, different configurations of tetrode arrays were designed respectively, as shown in Fig. 2. To hold the tetrode modules and balance the weight, a cross-shaped planar arrangement with 32 tetrodes positioned in each arm was applied. Two grounding wires were used for each module: one is to be attached to the skull and the other to the copper-mesh cage wrapped around the finished headstage after surgery.

Characteristic Signal Selection

To indicate how much a tetrode signal can represent the signal characteristics of its region, correlation strength is defined as follows:

$$R_{m,n}^{r} = corr(S_m^r, S_n^r) \tag{1}$$

$$RS_m^r = \frac{1}{N^r}\sum_{k=1}^{N^r} R_{m,k}^r \tag{2}$$

For *r-th* ($r \in (1, \cdots, 13)$) brain region, there are a total of N^r (N^r can be 8 or 16 shown in Table 2) tetrodes of LFP signals. RS_m^r denotes the correlation strength of *m-th* channel in *r-th* region, and $R_{m,n}^r$ represents the correlation between whole LFP signals S_m^r and S_n^r, which are the recordings from *m-th* and *n-th* tetrodes respectively, as shown in Fig. 3(a). Correlation is measured by Pearson Correlation. Finally, the tetrode signal with the highest correlation strength is chosen as the characteristic signal of the region, as shown in Fig. 3(b).

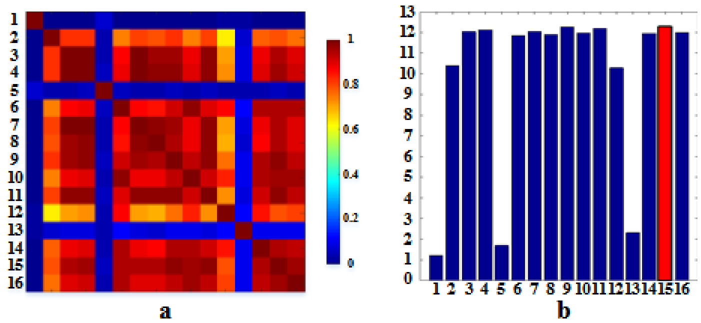

Fig. 3 Characteristic signal selection of a brain region (CA1).

Sparsity of Imaginary Part of Coherency

According to the concept of brain functional segregation and coordination, a few functional connectivities coordinate simultaneously and independently. Generally, a LFP time series $x_i(t)$ and its complex Fourier transforms $x_i(f)$ can be separated into three parts:

$$\hat{x}_i(t) = \sum \hat{x}_i^{FC}(t) + \sum \hat{x}_i^{VC}(t) + \hat{x}_i^{\varepsilon}(t) \tag{3}$$

$$x_i(f) = \sum x_i^{FC}(f) + \sum x_i^{VC}(f) + x_i^{\varepsilon}(f) \tag{4}$$

where $\sum \hat{x}_i^{FC}(t)$ / $\sum x_i^{FC}(f)$ are the components of functional connectivities which we are interested in, $\sum \hat{x}_i^{VC}(t) / \sum x_i^{VC}(f)$ are the artefacts of volume conduction from remote sources, and the last term is random noise. All signal components are independent. According to the definition of cross-spectrum, we can get:

$$\begin{aligned} S_{ij}(f) &\equiv \langle x_i(f) x_j^{*}(f) \rangle \\ &= \langle \sum \sum x_i^{FC}(f)\, x_j^{FC^*}(f) \rangle \end{aligned} \tag{5}$$

$$+\langle\left(\sum\sum x_i^{FC}(f)\,x_j^{VC^*}(f)+\sum\sum x_i^{VC}(f)\,x_j^{FC^*}(f)\right)\rangle$$

$$+\langle\sum\sum x_i^{VC}(f)\,x_j^{VC^*}(f)\rangle$$

$$+\langle\left(\sum x_i^{\varepsilon}(f)\,x_j^{*}(f)+\sum x_i(f)\,x_j^{\varepsilon*}(f)-\sum\sum x_i^{\varepsilon}(f)\,x_j^{\varepsilon*}(f)\right)\rangle$$

The last term includes noise components. As the noise is thought to be white Gaussian noise, therefore, the expectation of noise components is zero. If the two signals are independent, their phase difference is a random number and the cross-spectrum is zero (Nolte et al., 2004). Therefore, the cross-spectrum of different source signals can be omitted, and the second term is zero. As mentioned beforehand, volume conduction from same source does not cause time-lag, and the third term only has real part. Finally, the cross-spectrum mainly contains two components, and only the term of functional connectivity contains imaginary part.

$$S_{ij}(f)\equiv\langle x_i(f)x_j^{*}(f)\rangle=\langle\sum x_i^{FC}(f)\,x_j^{FC^*}(f)\rangle+\langle\sum x_i^{VC}(f)\,x_j^{VC^*}(f)\rangle \qquad (6)$$

$$FC^{B}(t)\sim\{C_{ij}(f,t)\}\sim Img(\{S_{ij}(f)\})\equiv Img\left(\sum\{\langle x_i^{FC}(f)x_j^{FC^*}(f)\rangle\}\right) \qquad (7)$$

In the view of signal component, the imaginary part of the coherency is a linear combination of those of all independent functional connectivities. Therefore, it is reasonable to apply sparse coding method to investigate the brain functional connectivity.

References

Nolte, G., Bai, O., Wheaton, L., Mari, Z., Vorbach, S., Hallett, M., 2004. Identifying true brain interaction from EEG data using the imaginary part of coherency. CLINICAL NEUROPHYSIOLOGY. 115, 2292-2307.