Dense EEG and dynamics of cognitive brain networks

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***Abstract*— Cognition is a network phenomenon. During cognitive activity, brain networks have to rapidly reorganize on a sub-second time scale. Tracking the dynamics of these networks over this short time duration is an unsolved issue. Here, we propose a new way to tackle this problem by using dense electroencephalography (EEG) recorded during a specific cognitive task: picture naming. We found that the cognitive task can be divided into six functional connectivity states (fcSs) characterized by significantly high synchronization of gamma (30-45 Hz) oscillations. We showed that dense-EEG can reveal the spatiotemporal dynamics of whole-brain functional connectivity at high temporal (in the order of ms) and spatial (~1000 regions of interest) resolution.**

Our results showed also that the brain cognitive functions are based on fast transitions between fcSs that last from 30 ms to 160 ms. Each identified network can be associated with one or several specific function (visual processing, lexical concept activation, selecting the target word from the mental lexicon, phonological encoding, phonetic encoding, and initiation of articulation) of the whole cognitive process. Finally, we believe that the identification of the dynamics of cognitive brain networks is a very powerful tool to understand the brain information processing.

***Index Terms*—Cognitive activity; EEG; brain networks**

I. Introduction

Cognitive functions involve the activation of a large-scale functional brain network. In visual, attentional and memory processes, this network is characterized by increased synchronization of cortical oscillations, in the gamma frequency range, in particular but not only, across distant neuronal assemblies distributed over distinct brain regions [1, 2].

Nowadays, a challenging issue in cognitive neuroscience is how to precisely identify brain networks at very short temporal scales. This short duration of many cognitive processes (<1s for picture naming, for instance) requires the use of techniques that provide a very high temporal resolution (on the order of ms), which is the case of the magneto/electroencephalography (M/EEG).

The main purpose of this abstract is to show a new neuroimaging method aimed at analyzing the spatiotemporal dynamics of functional brain networks during short duration cognitive task (< 1s). The key originality of the presented method is its ability to track brain dynamics with excellent temporal (at the order of millisecond) and spatial (~1000 regions of interest) resolutions using dense EEG recordings.

Our results reveal the presence of *switching behavior* of the brain networks during cognition and that even short cognitive process can be decomposed into a sequence of transiently stable and partially overlapping networks.

II. Methods

The different steps of the processing are illustrated in fig. 1. It starts by recordings the dense EEG signals during the cognitive task. The cortical sources are then reconstructed and the functional connectivity is then computed between the reconstructed sources to provide the functional networks which can be analyzed by network measures from graph theory-based analysis.

A. Picture naming

Twenty one right-handed healthy volunteers (11 women and 10 men), were involved in this study. Participants were asked to name 148 displayed pictures on a screen. This study was approved by the National Ethics Committee for the Protection of Persons (CPP), *conneXion* study, agreement number (2012-A01227-36), and promoter: Rennes University Hospital. The brain activity was recorded using dense-EEG, 256 electrodes, system (EGI, Electrical Geodesic Inc.). EEG signals were collected with a 1 kHz sampling frequency and band-pass filtered between 3 and 45Hz. Each trial was visually inspected, and epochs contaminated by eye blinking, movements or any other noise source were rejected and excluded from the analysis performed using the EEGLAB open source toolbox.

B. EEG source connectivity

To compute the brain networks, we used the combination of weighted Minimum Norm Estimator (wMNE) for source localization method and the Phase Locking Value (PLV) as connectivity method applied on the dense EEG at gamma frequency band (30-45 Hz). This combination provided the best performance to study functional connectivity at source level as shown in [3].

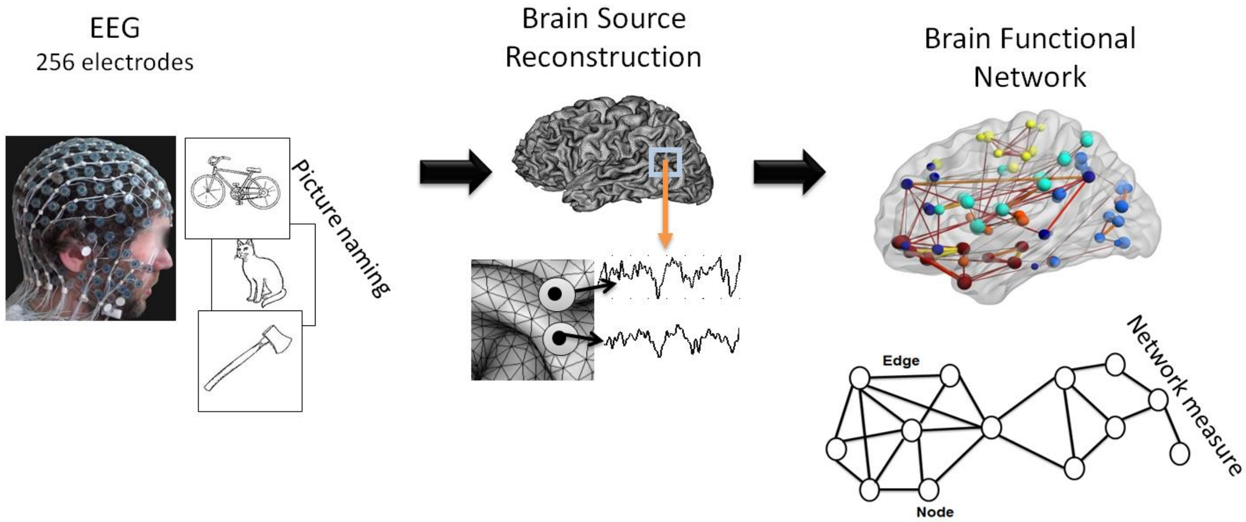

Figure 1 : Pipeline of the method. Dense EEG signals are recorded using 256 electrodes during a cogntive task: picture naming. The brain sources were reconstructed using inverse problem algorithm. The brain networks were then obtained by computing the functional connectivity between the reconstructed sources. These networks can be then charcerized using network mesures.

C. Functional connectivity states

We recently developed an algorithm to decompose cognitive task into functional connectivity states (fcS). The objective of this algorithm was to identify clusters among all the possible networks. The proposed algorithm is based on the *K-means* clustering of the connectivity networks obtained by the PLV method. This approach allowed us to summarize brain networks into a limited number of dominant networks over given time period. See [4] for more details about the algorithm.

III. RESULTS AND DISCUSSIONS

The main findings are shown in figure 2. The figure shows the six functional connectivity states (fcSs) obtained from the picture onset to the naming process. The identified networks (locations and timing) corroborate previous studies based on other modalities, mainly fMRI, MEG and PET [5, 6]. In addition, they show a *switching behavior* of the brain networks at very short time scale.

For the first fcS (fcS1, 0:119 ms), results showed a network involving the inferior occipital, the lateral occipito-temporal sulcus and occipital pole. This period corresponds to the first visual processing of the presented picture while the stimulus is probably not recognized yet. It corresponds to the visual feature extraction preceding the object category recognition [7].

Interestingly, the visual features obtained by Vanrullen et al. revealed response peaking at 120 ms after the onset which is very comparable to our limit for the first fcS (119 ms). For fcS2 (120:150 ms), the identified functional network mainly comprises the occipital regions (the bilateral inferior occipital, the left occipital pole, right anterior occipital and the left middle occipital and Lunatus). These regions are well known to play a capital role in the processing of visual information and object recognition. Also, the gamma in this time period was revealed as indicator of object recognition [8, 9].

For fcS3 (151:190 ms), results indicate a mainly occipital network but with an implication of the bilateral inferior temporal sulcus. This system is known to be related to lexical retrieval, lemma retrieval and lemma selection. It is also involved in semantic processing when someone tries to remind the name of the objects [10]. In their study, the authors show a discrepancy in the temporal lobe involvement for objects versus animals with more activity in the inferior temporal sulcus for objects and in the superior temporal sulcus for animals. Our picture set comprises 39 animals versus 109 objects or non-animal images. The dominant representation of objects in our experimental set could have shaped this part of the graph favoring the inferior temporal sulcus at the expense of the superior temporal sulcus.

During fcS4 (191:320 ms), the network involves the left inferior temporal gyrus in addition to the inferior temporal sulcus. These regions were stated to be in direct relation to semantic processing [10]. It is also the time window in which the N200 classically appear. The N200 is a marker of semantic processing in go/no-go tasks [7].

Together with the appearance at this stage of frontal nodes, we interpret that this large fcS could also integrates the access to phonological forms during overt naming which has been shown by Graves et al. [11]. In a somewhat interesting way, we found that this fcS ends 10 ms before the syllabification step in the model of Indefrey and Levelt [12].

At fcS5 (321:480 ms), the functional network involves the left superior precentral and the right postcentral sulcus along with the left orbital sulci and the left superior insula. This network, near to the sensory-motor cortex was reported to be engaged into phonetic and articulatory process of speech [5, 13].

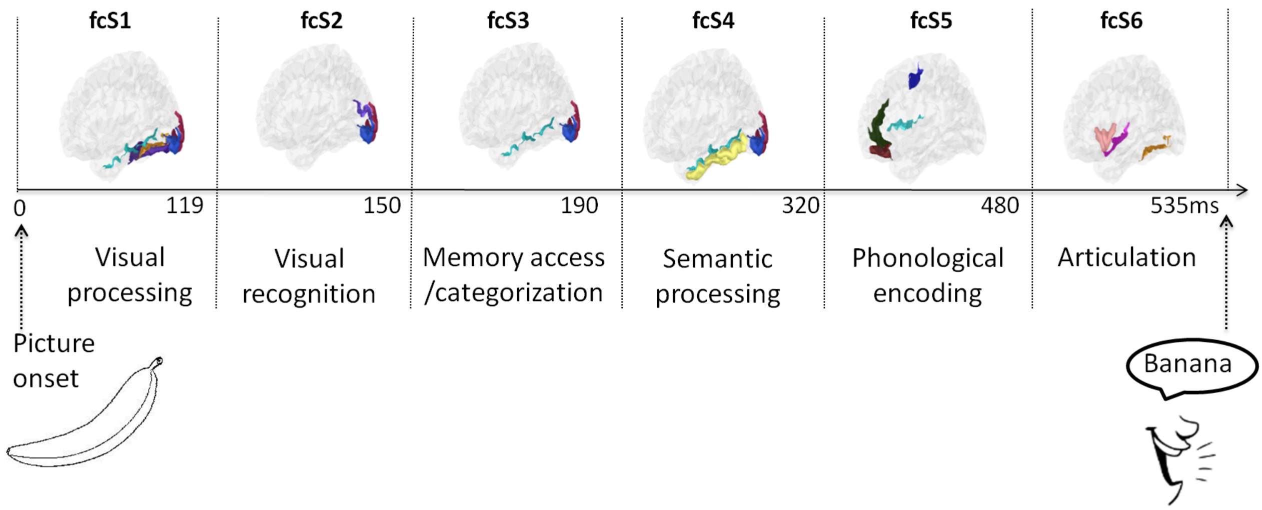

Figure 2 : The identified regions (based on graph theory analysis) are color-coded based on the anatomical parcellation of Destrieux Atlas using Brainstorm Tool [14]. The underlying cognitive functions for each fcS is presented. fcS: functional connectivity state.

Finally, for the last fcS (fcS6, 481:535 ms), the network was found at the left insular gyrus, the left inferior insular circular sulcus and the right orbital sulcus. This network is typically associated with the beginning of the naming process and the speech articulation as well as listening to own speech (external self-monitoring) [5, 12].

CONCLUSION

Here, a new method aiming at tracking the spatiotemporal dynamics of brain networks over a short duration cognitive task (<1 second) from scalp EEG data is proposed. The obtained results go beyond those obtained with classical neuroimaging techniques such as fMRI, as the proposed method offers the unique advantage to track the network dynamics with high temporal (in the order of ms) and spatial (~1000 ROIs) resolution.

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