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Changes in connectivity and local synchrony after cognitive stimulation – Intracerebral EEG study

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ABSTRACT

Electroencephalographic studies utilize event-related power decrease/increase in order to analyze changes of neuronal activity in a single EEG channel during cognitive tasks. Other analytical approaches draw on bivariate methods which evaluate connectivity between two EEG channels. Despite the fact that spatial mapping of combined results of power and connectivity analyses may be used to study the dynamics of neuronal activation patterns, they are normally evaluated separately as different phenomena. Here we show the evaluation of dynamic changes in linear correlation after cognitive stimulation together with changes in power levels in the same channel pairs. Our results demonstrate the temporal evolution of synchronization patterns across the whole brain with a focus on the anatomical structure of the hippocampus. We observed a pattern of local and distant synchrony during cognitive processing, occurring 500 ms after stimulus onset in approximately 1% of all channel pairs. We hypothesize that evaluation of changes in connectivity, together with dynamic changes in power levels, can help identify dominant structures in the process of mental activity after a certain type of cognitive task. This can possibly lead to better understanding of synchronization processes at the neuronal and systemic level.

1. Background

Human brain dynamics are characterized by a sequence of synchronization patterns evolving within the constraints of the anatomical framework [1]. Covariation of these synchronization patterns is often described as the functional connectivity of the brain. Despite extensive literature covering this area, there are still gaps in our knowledge about the spatial and temporal mechanisms involved in neuronal synchronization processes after cognitive tasks [2,3].

Human brain connectivity can be studied by intracerebral electroencephalographic methods (stereo EEG – SEEG). Depth electrodes are able to detect the local cooperative electrical activity of neuronal populations, described as local field potentials (LFPs) [4,5].

After stimulus presentation, for a short period of time, electrical activities of LFPs measured by intracerebral depth electrodes in different neuronal populations synchronize their phases and simultaneously change their power levels [6,7,8]. These phase-locked reactions which occur after cognitive stimulation can be measured by a single SEEG electrode and are described in the literature as event-related potentials (ERP) [9,10].

In contrast, changes in local power levels after stimulus presentation that are not phase-locked to the event can be described as event-related synchronization (ERS, power increase) or event-related desynchronization (ERD, power decrease) [11].

Additionally, similarities in signal shape between two SEEG channels can be calculated by, for example, correlation. An increase in correlation after cognitive stimulation is then interpreted as an increase of connectivity in the given pair of SEEG channels [12,13,14,15].

A decrease in local power after cognitive stimulation, ERD, is often accepted as proof of mental activity [16]. Similarly, an increase in connectivity between SEEG channels is mostly interpreted as an increased involvement in cognitive processes. However, these two phenomena (connectivity and power) are never evaluated together as one congruent state [17,18,19,20].

The aim of this work is to show that the connectivity between two SEEG channels can be examined together with their instan-

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Table 1
Patient characteristics.

Subject	Age	Gender	Dominant hand	Implanted sites*	Number of analyzed channels
1	36	M	R	LFP, RFP	86
2	24	F	R	RFTP	74
3	41	M	R	LFTP, RFTP	78
4	23	M	R	LFPTO, RFTP	47
5	29	M	R	LTPO, RTP	79
6	17	M	R	LFP	53
7	41	F	R	LFTP	78
8	29	F	R	LT, RT	49
9	28	F	R	LT	31

* T, temporal; F, frontal; P, parietal; O, occipital; R, right; L, left.

taneous power levels, calculated in the manner of ERD/ERS in different frequency bands [11].

We detected four different states after cognitive stimulation. 1 – correlation increase with simultaneous power increase, 2 – correlation increase with power decrease, 3 – correlation decrease with power increase, and 4 – correlation decrease with power decrease.

Evaluation of these phenomena can provide comprehensive information leading to a better understanding of the connectivity principles at the spatial level of LFPs measured by clinical depth electrodes. Spatial mapping of dynamic changes in connectivity and simultaneous power changes brings a new insight into the functional connectivity of cognitive networks and can help identify dominant structures in the process of mental activity after a certain type of cognitive task.

2. Methods

2.1. Subjects

A dataset of nine subjects (five males, four females), aged between 17 and 41 years (mean 28.9 years, std. 8.21), participated in this study (Table 1). All subjects suffered from medically intractable, temporal lobe epilepsies. Standard semi-flexible ALCIS electrodes (0.8 mm diameter) with a 2 mm contact length and a 1.5 mm space between contacts were implanted in order to localize the origin of seizure before the surgical procedure. The placement of each electrode was verified by an MRI scan. Talairach stereotactic coordinates were used [21]. Each subject received between 6 and 15 orthogonal electrodes (95 multicontact depth electrodes). The implantation sites (898 in total) included the temporal, frontal, parietal and occipital lobes. Pathological structures were omitted from the analysis. Each subject received a reduced dose of anticonvulsant medication during the experiment. All subjects understood the experimental task.

2.2. Visual oddball task

The subjects sat in a room with a screen placed 100 cm in front of their eyes. They were asked to concentrate on a point in the middle of the screen and reduce their frequency of blinking. Frequent and target stimuli were shown in random order. The frequent stimuli were presented as a capital 'O' and the target as an 'X'. The duration of each stimuli was 500 ms and the frequent:target ratio was 4:1. The interval between stimuli changed randomly between 4 and 6 s. Each subject was asked to react to the target stimuli as fast as they could by pressing a button.

2.3. SEEG recordings

Intracerebral SEEG was recorded by a 128-channel TrueScan EEG system (Deymed Diagnostic) with a common reference on the earlobe. Eye movement was simultaneously recorded by standard EOG electrodes placed near the left and right eyes. All recordings were sampled at 1024 Hz and filtered by standard anti-aliasing filters (cut-off frequency 350 Hz). Artifacts in the recorded data were detected manually and omitted from further analysis.

2.4. Signal pre-processing

To suppress far-field potentials caused predominantly by volume conduction, bipolar montages were calculated before filtering as the difference between two neighboring contacts on the multicontact electrode: $A_i = A_i - A_{i+1}$. The measured data was downsampled to 256 Hz and filtered in six frequency ranges, δ (2–4 Hz), θ (4–8 Hz), α (8–12 Hz), β (12–20 Hz), lower γ (20–45 Hz) and upper γ (55–95 Hz). Filtration was performed on full-length signals by selecting a frequency region in frequency spectra after detrending and tapering the time signal. The result of this process were signals filtered as time signals which we used for correlation analysis. For event-related power analysis, signals were filtered as power envelopes (Hilbert transformation) (Fig. 1-A). Segmentation of filtered data was performed according to stimuli position. The length of each segment was 8 s with the onset of the stimulus placed in the middle. Two types of segments were distinguished: target and frequent. The number of trials was approximately 50 for targets and 200 for frequents. The total number of frequent trials was randomly reduced to attain the same number as for targets for the purposes of analysis.

2.5. Correlation

The time evaluation of correlation was applied to determine the shape similarities in all pairs of channels using sliding windows moving over the total length of signals, 500 ms wide with a 50 ms step. Pearson's correlation coefficient was calculated for each step of windows as: $\rho_{X,Y} = (cov(X, Y)/\sigma_X\sigma_Y)$, where X,Y are the two evaluated signals, ρ is the correlation coefficient, cov is the covariance and σ is the standard deviation. The sliding windows were multiplied by a hamming function at each step to reduce the influence of the border area [1,12].

2.6. Correlation – statistics

Significant pre-stimulus-related changes in the correlations in every channel pair were found by comparing the levels of the correlation from the baseline to the levels of the correlation after stimulus onset from all target or frequent trials. The baseline was 500 ms in width; it began at 600 ms and ended at 100 ms before stimulation. The statistically significant differences between the median value from the baseline and correlation values after stimulus onset were calculated by the paired non-parametric Wilcoxon signed rank test. The difference was marked as significant for $p < 0.01$, Fig. 1-B. A significant change of the absolute values of the correlation after stimulus onset was then considered to be either an increase (shape similarity) or a decrease (shape diversity). Fig. 2 shows an example of a matrix with significant correlation increases in the 300–400 ms interval after stimulus onset in all channel pairs. The values in the matrix represent the duration of significant change in the observed 100 ms interval. The duration was in the <0,1> range, where 0 means no significant change and 1 means a significant change during the whole observed interval.

2.7. Power

The power envelope of LFPs measured by every single SEEG channel was determined from the analytical signal which was previously calculated by the Hilbert transformation (see Section 2.4