Oscillatory hierarchy of human brain rhythms and excitability: intracranial micro- and macro-electrode recordings in the temporal cortex

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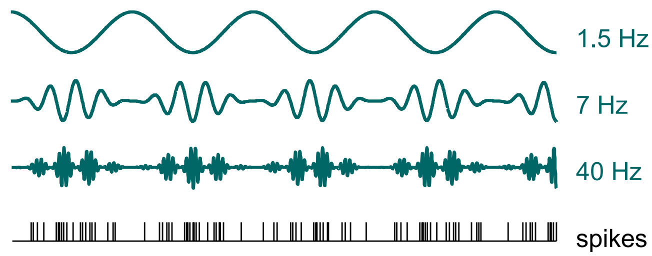
Introduction

- Hierarchical organization of brain rhythms (e.g. Lakatos et al., 2005)



- Also shown in human intracranial data : e.g. between theta phase and high-gamma amplitude (Canolty et al., 2006)

Recordings of the spontaneous activity in the monkey auditory cortex have shown that brain rhythms are hierarchically organized

For example Lakatos and colleagues have shown that the phase of the delta rhythm modulates the amplitude of the theta rhythms

And that in turn, the theta phase determines the amplitude of gamma rhythms

They've also shown that this oscillation hierarchy controls excitability as measured by the multi-unit-activity

In human intracranial EEG, several studies have shown phase-amplitude coupling of oscillations, for example between the theta phase and the amplitude of high gamma oscillations

However, to the best of our knowledge it has never been shown in the human that oscillations controlled neuronal firing

Goals

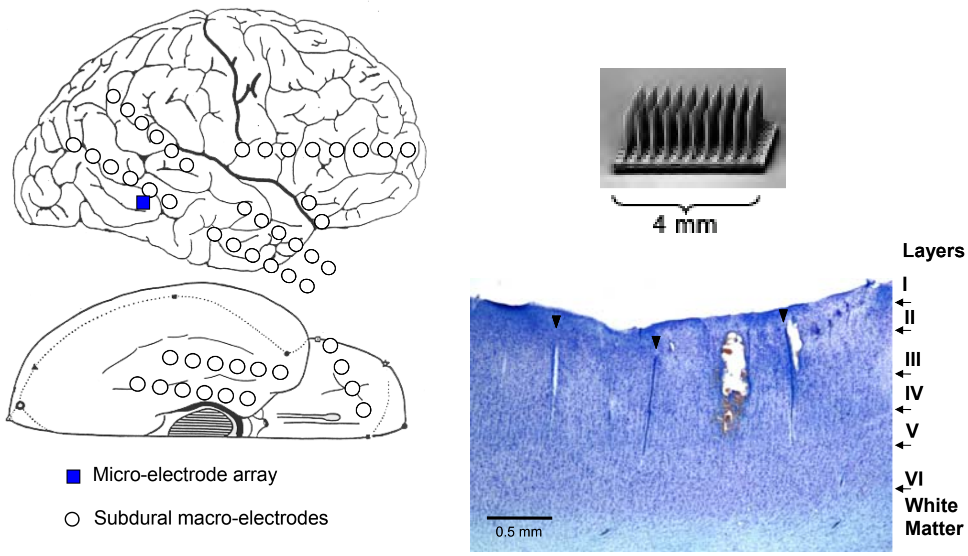
- Establish coupling between oscillations and excitability using human micro-electrode recordings
  - MUA as a measure of neuronal firing
- Extend analysis of phase-amplitude coupling to a wider range of frequencies in human spontaneous LFPs
  - Phases from .1 to 20 Hz
  - Amplitudes from 1 to 250 Hz

Our goal was to establish a link between LFP oscillations and excitability using micro-electrode recordings in the temporal cortex

We used the multi-unit activity as a measure of neuronal firing (it is obtained by filtering the LFP above 500 Hz and reflects the firing of a population of neurons)

The other goal was to extend the analysis of human spontaneous oscillations to a wider range of frequencies : we tested the coupling between phases from .1 to 20 Hz and amplitudes from 1 to 250 Hz

Recordings

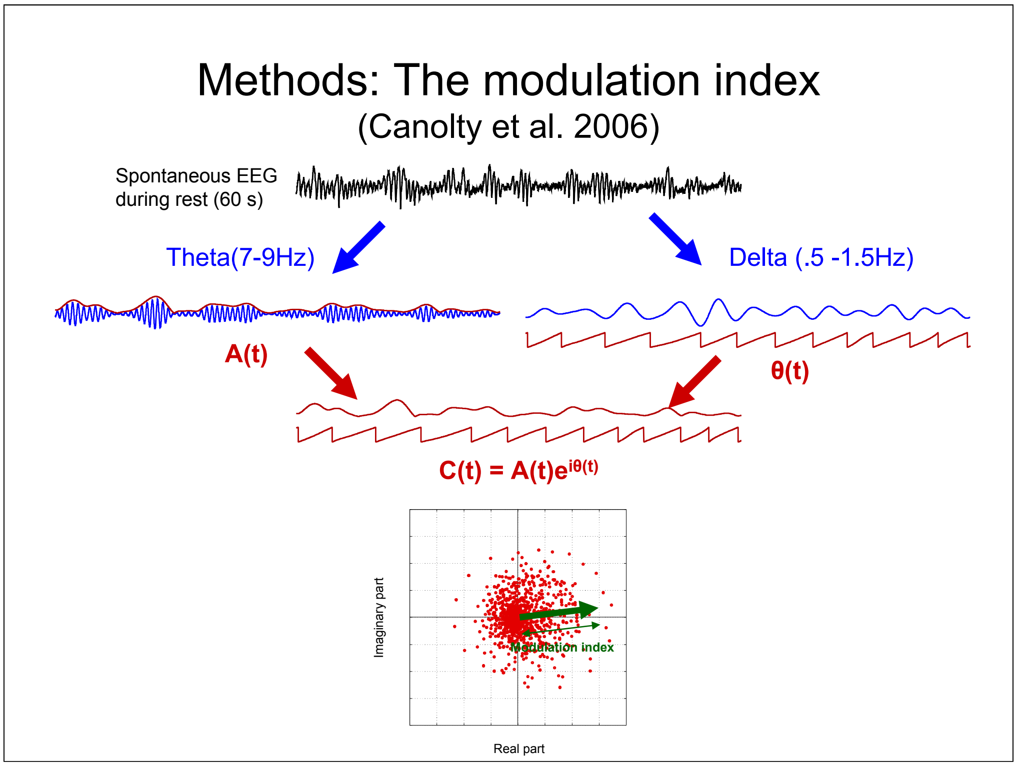


Post-implant histopathology

We will report recordings from an epileptic patient implanted both with subdural macro-electrodes
Strips of subdural electrodes covered the temporal lobe, the frontal lobe and the sub-temporal lol

This patient was also implanted with an array of 96 micro-electrode in the middle of the temporal
But it turns out that the eeg recorded at those electrodes was not pathological, as far as epileptol

The micro-electrode implant is an array 10 by 10 microelectrode. Electrodes are spaced by 400 r
Histopathological dying made after the resection of the cortex from another patient shows that th



To detect coupling between the phase of one given frequency and the amplitude of another frequency, we used the modulation index introduced by Canolty and coworkers.

The analysis was performed on a rest period of 60 s

For each pair of frequencies , say delta and theta, we filtered the signal in these two frequency bands

We then computed the hilbert transform to obtain the phase of one frequency and the amplitude of the other

We then combined those phases and amplitudes in a new complex signal

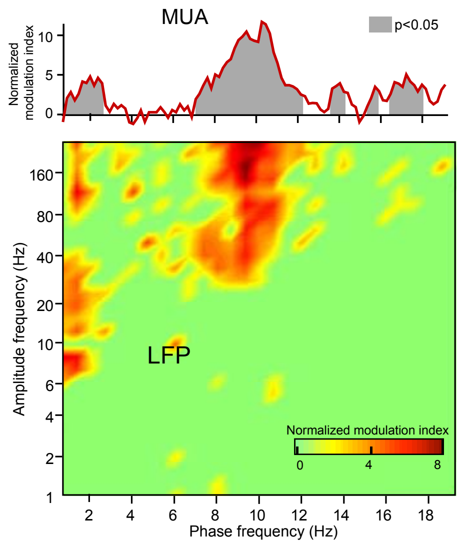
The modulation index is the averaged complex number across all time samples (that is the average of the phases weighted by the corresponding amplitude).

Here I plotted all time samples in the complex plane

If there is a preferential coupling between a given delta phase and the maximum of gamma amplitude, then the average will be a bias in the direction of the preferred phase and the length of the resultant vector should be greater than zero

In this example, there was a higher theta amplitude for a delta phase of about 0

Results: Modulation index over 60s of spontaneous EEG (micro-electrode)



Here I plotted the modulation index for all phase/amplitude pairing at one of the micro-electrodes of the array

There was a significant coupling between low delta phase (below 2Hz) and the amplitude of several frequency bands: theta, beta/gamma and high gamma

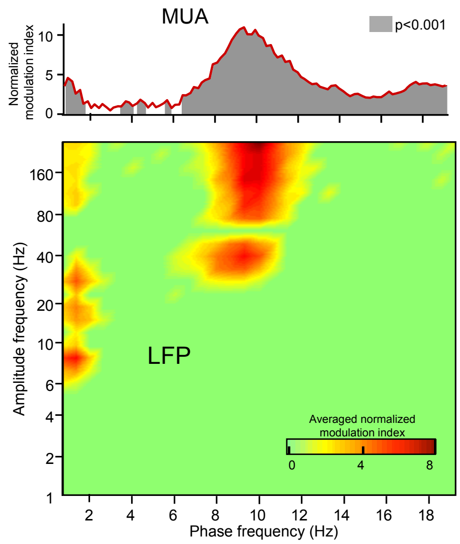
And there was a significant coupling between alpha phase and low/high gamma amplitude

We also computed the modulation index between all phases from .1 to 20 Hz and the amplitude of the MUA

There was a significant coupling between the phase of delta oscillations and the alpha oscillation and the MUA amplitude

Which shows that delta and alpha oscillations control excitability

Results: consistency over 20 periods of 60 s (micro-electrode)



What we did next is to try to assess the reproducibility of the result over a longer period of time. We took 20 consecutive periods of 1 minutes,

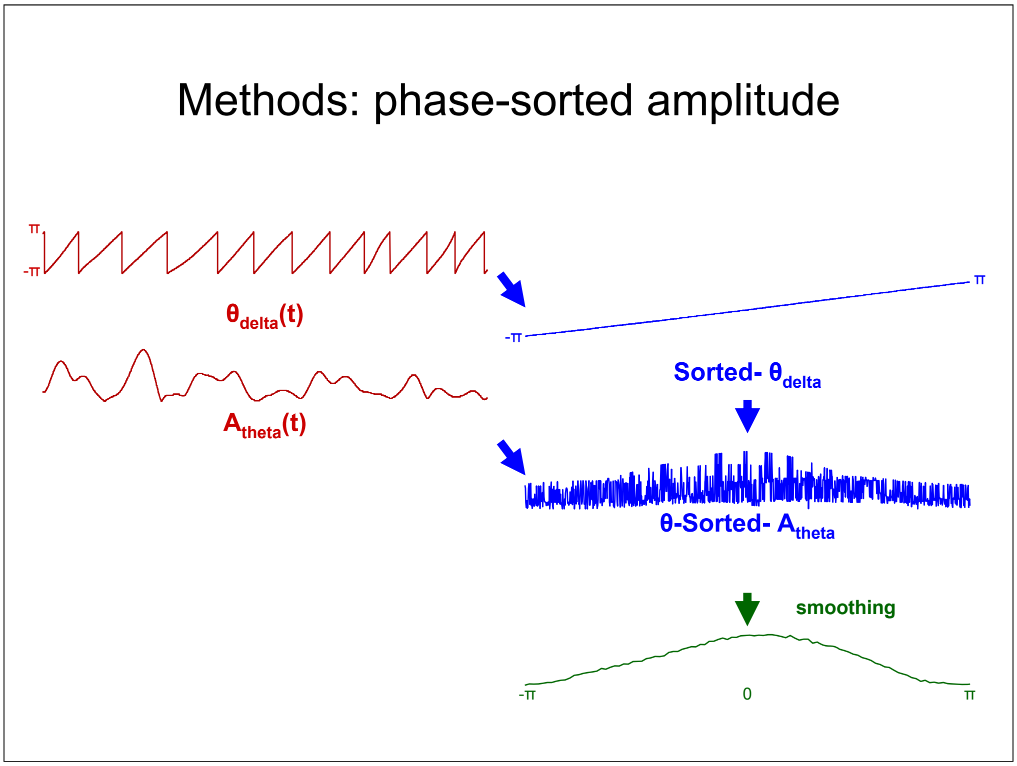
Computed the modulation index for each of them for all phase and amplitude frequencies and computed the mean over the 20 values

We also conducted a t-test at all phase/amplitude pairs

And I'm only showing mean values that were significantly different form zero at a .001 level

Basically, all the coupling that I reported before were consistent across the 20 different blocks, both for LFPs and MUA

To further characterize these different coupling, we used the phase-sorted amplitude technique used by Lakatos and colleagues.



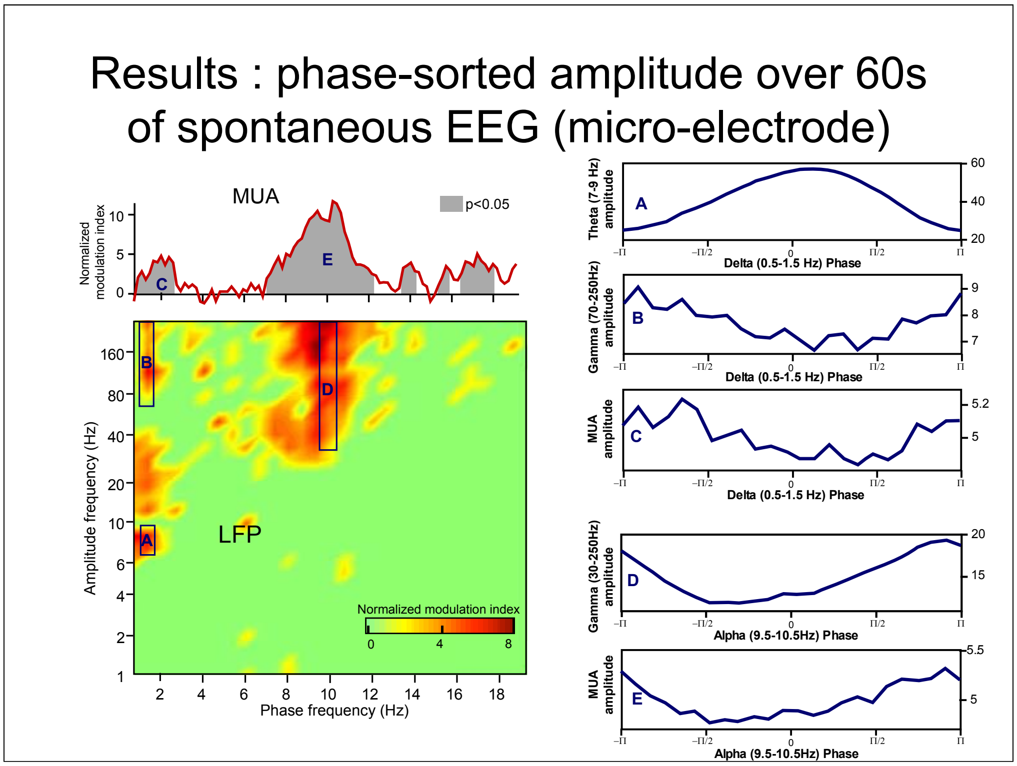
Let's return to our previous example: we have this delta phase and this theta amplitude and we want to know what is the delta phase with the more theta amplitude and what is the delta phase with the worst theta ampllitude

So we're gonna sort the phases from the lowest to the highest phase value

And use this re-ordering of phase to re-order the amplitudes,

This usually gives something quite noisy, so we had to smooth it.

In this example, there was a stronger theta amplitude just after the zero phase and a smaller amplitude at the pi-phase



This is the phase-sorted amplitude for delta phase and theta amplitude: the theta amplitude was maximum just after the delta rhythm was in its positive phase

We also looked at the beta gamma/amplitude and found the same relationship.

If we now look at the coupling between delta phase and high gamma amplitude (between 80 and 250 Hz), it goes the other direction: high gamma amplitude is larger just after the negative peak of the delta oscillation

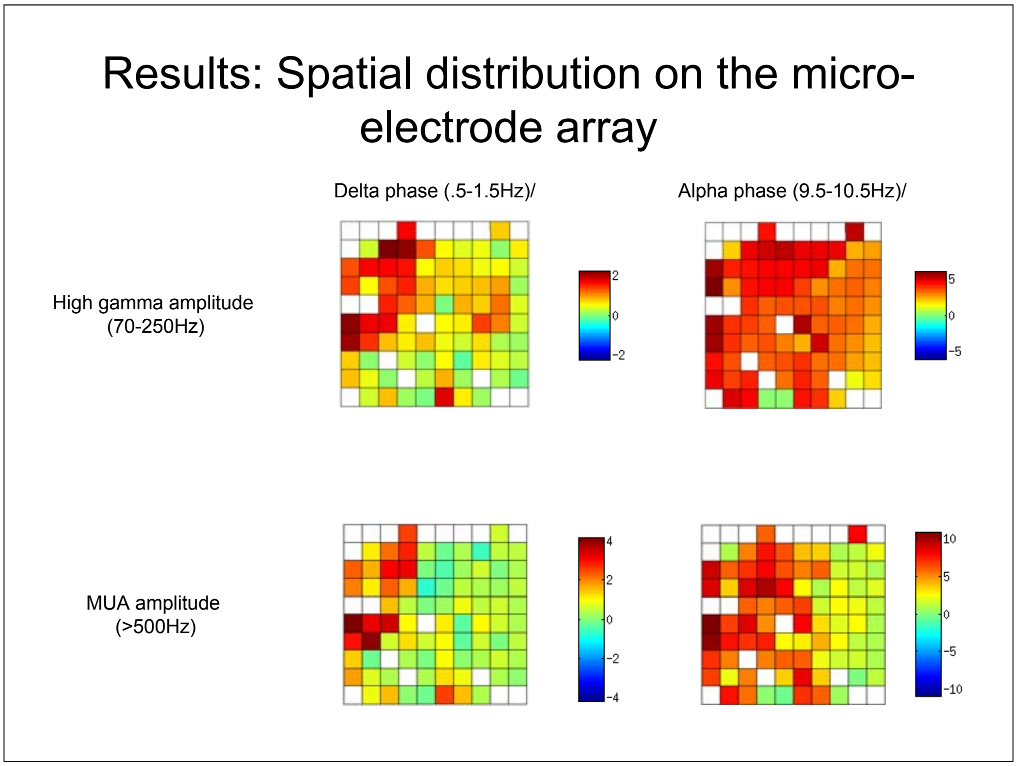
This shows that when theta goes down, gamma goes up

We also phase-sorted the multi-unit activity amplitude: it gives the same relationship to delta phase as the high gamma

For alpha phase, both gamma and mua amplitude maximum just before the negative peak of the alpha oscillations

So in both cases of the delta and alpha oscillations, the high gamma and the MUA were maximum for the same phase

This suggests that high gamma and multi-unit activity may reflect a common phenomenon and that high-gamma reflects excitability



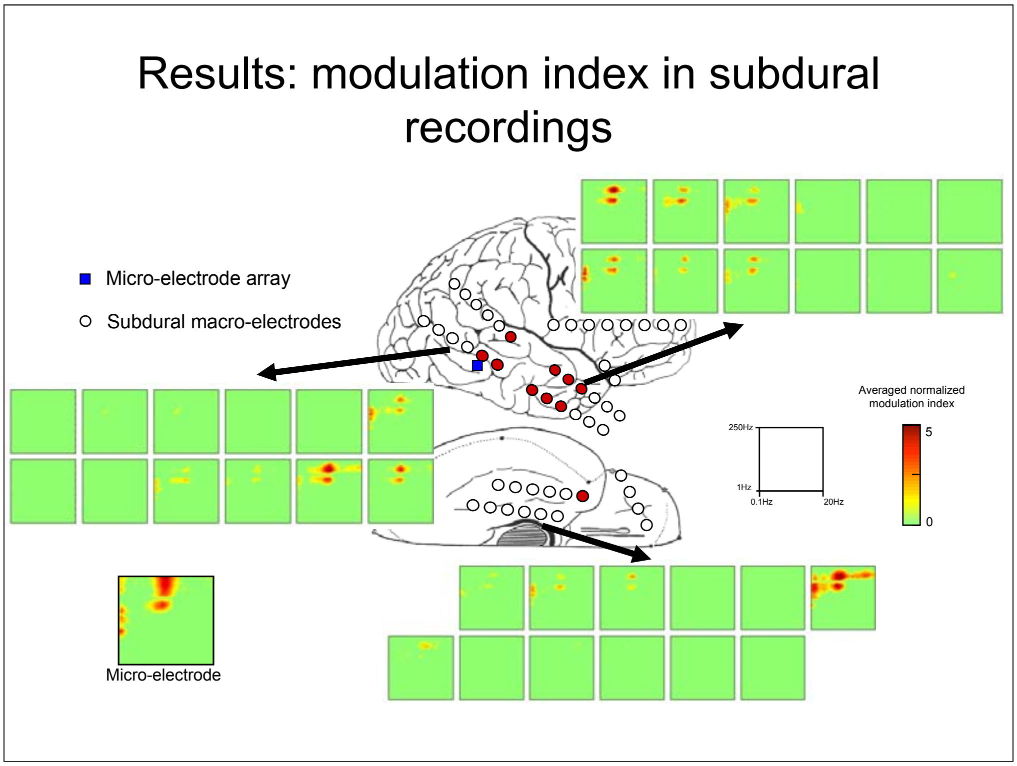
Next we looked at the topography of these couplings on the array to look at any sign of columnar organization

I focus here on the high-gamma coupling to delta and alpha phase

In both case, there was some hint of a columnar organization, the coupling being stronger for the upper left corner of the array

But it could also be that if the array was slightly slanted relative to the cortical layers and the right electrodes are in a different layer

If we now look at the coupling of MUA with alpha and delta phase, we found the same topography, which again suggests that high gamma and MUA index the same phenomenon



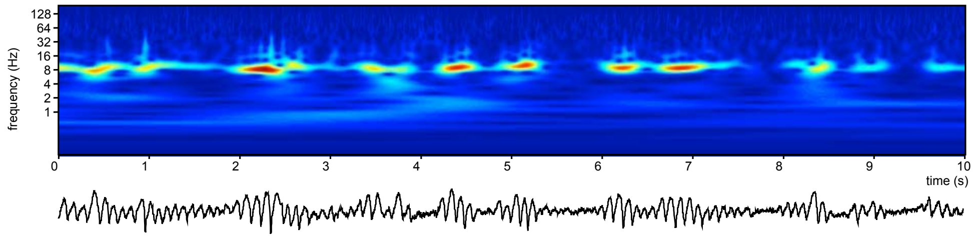
Finally, we computed phase-ampllitude coupling on the potentials recorded on the subdural electrodes to get a better idea of the spatial distribution of the phase-amplitude coupling on the temporal cortex

We found the significant couplings only for temporal subdural electrodes, here in red

The coupling between delta phase and high gamma was not significant, but except fpr that, the overall configuration of coupling on these electrodes was similar to the one found on the micro-electrode array

This temporal region was precisely the one which a prominent alpha activity was recorded

Raw microEEG



- The temporal lobe alpha rhythm
- Only recorded with temporal intracranial electrodes, but not considered pathological (Niedermeyer, 1991)
- Not a clear functional role (auditory idling rhythm ?)

This is the spontaneous eeg from one of the microelectrode with its wavelet decomposition, but it was similar on the subdural EEG: the alpha rhythm is dominant in the spectrum and you can see that its power is modulated at a delta rhythm

This rhythm is actually well known in clinical neurophysiology as the temporal lobe alpha rhythm: It is considered a normal alpha rhythm, but can only be recorded with intracranial recording over the temporal cortex

As of today, it is not clear what is its function

There have been some attempts to relate it to an idling rhythm of the auditory cortex, similar to the occipital alpha rhythm for the visual modality

What I just want to point out her is that the phase-amplitude couplings we reported might be specific to this rhythm.

Discussion

- Phase-amplitude coupling in the human temporal cortex between:
  - Delta phase and theta amplitude
  - Delta phase and gamma/MUA amplitude
  - Alpha phase and gamma/MUA amplitude

→ Human brain oscillations are hierarchically organized and modulate excitability

→ High gamma may index excitability

To sum up, we found significant and consistent phase-amplitude couplings in the human temporal between:

Delta phase and theta amplitude

Delta phase and gamma/MUA amplitude

Those couplings were in opposite in directions

We also found a coupling between alpha phase and gamma and multi-unit activity amplitude

In all cases high gamma and multi-unit activity were coupled in the much the same way to lower-frequency oscillation phase

thus we showed that in the human brain too, brain oscillations are hierarchically organized and are linked to neuronal excitability

We've also shown that the amplitude of high-gamma oscillations may be used as an index of neuronal firing and excitability.

Our results may be restricted to the temporal alpha rhythm, the so-called third rhythm

We haven't found any difference of phase/amplitude coupling in a motor task compared to rest

Thank you for your attention