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# Phase transitions in the human brain revealed by large SQUID arrays: Response to Daffertshofer, Peper and Beek

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## 1. Introduction

In their Letter [1], Daffertshofer, Peper and Beek (referred to in the following as DPB) report on findings from an attempt to replicate an experiment by one of us (S.K.) in 1989 which demonstrated a phase transition at both brain (MEG) and behavioral levels of description [3,10,12]. Although DPB reproduce most of the original results, they fail to observe a frequency doubling in the brain signals which occurs across the transition. This apparent absence triggers a lengthy discussion of possible artifacts that may happen in spectral analysis of time series in the presence of noise. Here we show the results of our own replication of the original experiment using a state of the art full-head magnetometer in order to illustrate our point of view with respect to the arguments made in DPB. We find that the results from our earlier and recent experimental studies are in excellent agreement even though they use different subjects. Moreover, our results agree with well-established features of evoked auditory and motor fields in the neurophysiological literature whereas it

is not clear to us how the findings of Daffertshofer et al. fit into this picture.

## 2. Comparing the experiments

In all three experiments (the original, DPB and our recent one) a transition in coordination behavior from syncopation to synchronization [11] was used to prepare and probe neural activity in human subjects. The subjects' task was to perform a flexion movement of the preferred index finger in between two consecutive tones of an auditory metronome, i.e. to syncopate with the stimulus. It is well-known that by increasing the presentation rate of the stimuli as a control parameter a point is reached where subjects can no longer perform a stable syncopated coordination pattern and, under the instruction to keep pace with the metronome, switch spontaneously to a movement that is instead synchronized with the stimulus.

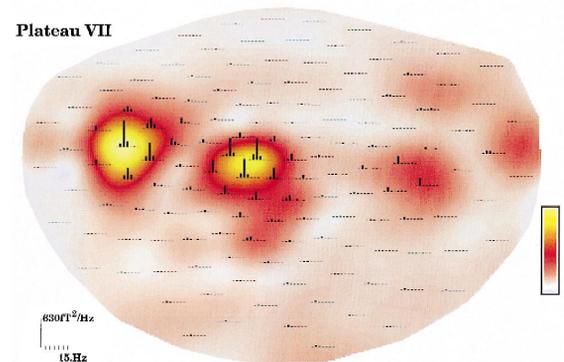
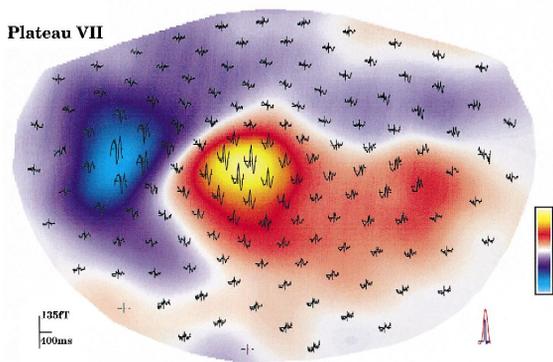
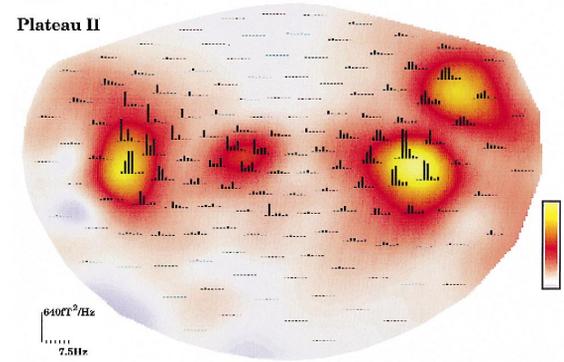
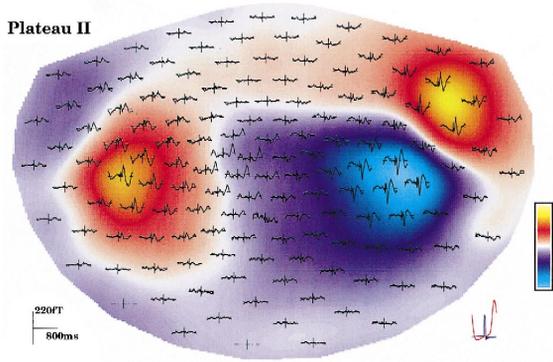
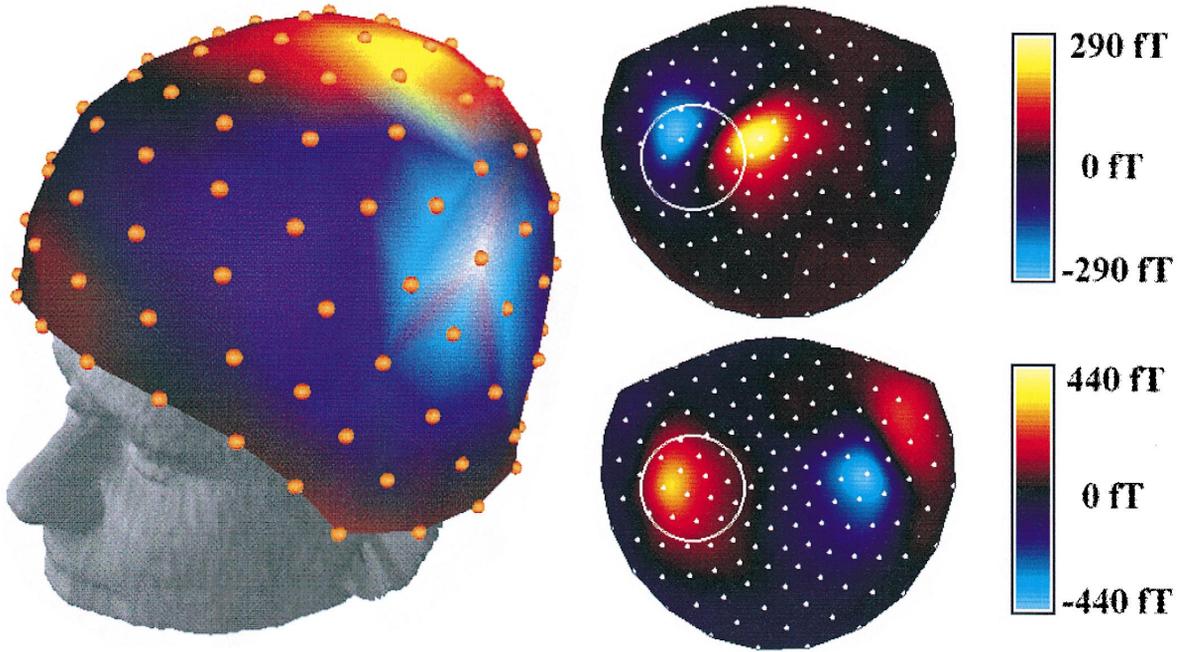
In 1989 MEG technology was not as developed as today and full-head magnetometers did not exist. The SQUID array used was a 37-channel device (BTI, Inc.) that covered a restricted portion of one hemisphere of the subject's brain. In our recent experiment a 143-channel system (CTF, Inc.) was used that gives access to activity over both hemispheres [13].

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The magnetometer used in DPB has 151 MEG-channels but is essentially the same device. Fig. 1 shows

the placement of the sensors over the subject's head during our recent recordings together with a polar



projection of two typical (average) activity patterns from control conditions, i.e. finger movement only (top) and auditory only (bottom). In these projections the nose is on the top of the display. White circles indicate the approximate area that was covered by the 37-channel device over the left auditory and motor cortex in the original study. There we reported three major changes in brain activity that take place when the switch in the movement behavior occurs:

1. the topography of the dominant spatial pattern of brain activity is different;
2. the frequency of the time-dependent amplitude of neuromagnetic activity corresponding to this pattern switches from the coordination frequency (prior to the transition) to twice the coordination rate (after the transition);
3. in certain sensors the time series undergoes a phase shift of  $\pi$  co-temporaneously with the transition in the coordination behavior.

Subsequent theoretical work established the nature of the phase transition at both brain and behavioral levels through phenomenological modeling [7]. More recently, a theory connecting brain and behavioral levels of description has been developed based on known cellular and neural ensemble properties of the cerebral cortex [4,8,9,14].

### 3. Results from our recent experiment

Our results from the 143-channel device are summarized in Figs. 2–5. Fig. 2 shows the average time series in all sensors ( $N \approx 120$  after behavioral editing and artifact rejection) for one coordination cycle

prior to the switch in behavior (frequency plateau II, 1.25 Hz) and following the switch (plateau VII, 2.5 Hz). Underlaid in color is the spatial pattern at maximum amplitude, i.e. 90 ms and 45 ms after stimulus onset for pre- and post-transition, respectively. Red, yellow corresponds to regions where the magnetic field lines exit the head; blue indicates that field lines are entering the head. On plateau II two dipolar patterns can be identified, one over each hemisphere with the dipole character over the right hemisphere more pronounced. This pattern is quite similar to the one recorded during the auditory control condition shown in Fig. 1 (right bottom). The spatial pattern on plateau VII is dominated by a dipolar-like field over the left hemisphere, contralateral to the right finger movement similar to the pattern from the motor-only condition in Fig. 1 (right top). This is the change in the spatial pattern reported in our earlier work. Notice in Fig. 2 that after the transition (plateau VII) the time series from sensors inside the motor dipole (where the amplitude is largest) have two maxima and two minima in each cycle and evidently oscillate at a frequency that is twice the rate of coordination.

Fig. 3 shows a closer investigation in terms of power spectra calculated from the time series displayed in Fig. 2, underlaid with the spatial patterns of absolute power on the same frequency plateaus. Prior to behavioral switching on plateau II there is a strong frequency component at the coordination rate in most sensors over contralateral motor cortex. (A fuller discussion of the right hemisphere data will be presented elsewhere [5] since this area was not recorded in the original experiment.) As expected from the time series the spectra over the left side of the head on plateau VII are dominated by the frequency component at twice the coordination rate.

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Fig. 1. (Upper half) Magnetic activity on a subject's head (left) and in polar projection (right). Red, yellow areas indicate where the magnetic field lines exit the head; in the blue regions the field lines enter. Left: Subject's head reconstructed from an MRI scan with magnetic brain activity associated with a right finger movement superimposed. Maximum amplitude is located over the contralateral area of the left hemisphere as expected. Right top: The same activity pattern (motor-evoked field) projected into polar coordinates (the nose points up). Sensor locations used in the present experiment are indicated by dots; the circle shows the approximate area which was covered by the 37-channel device used in the original experiment. Right bottom: Polar projection for an auditory-evoked field. Fig. 2: (Lower half, left) Time series of magnetic brain activity in single channels in topographic sensor layout for the syncope condition on plateau II (top) before the transition and plateau VII (bottom) post-transition underlaid with the spatial patterns at the time of maximum activity (90 ms and 45 ms after stimulus onset for plateaus II and VII, respectively). Fig. 3: (Lower half, right) Power spectra obtained from the time series for the syncope condition on plateau II (top) and plateau VII (bottom) underlaid with the spatial patterns representing the total power.

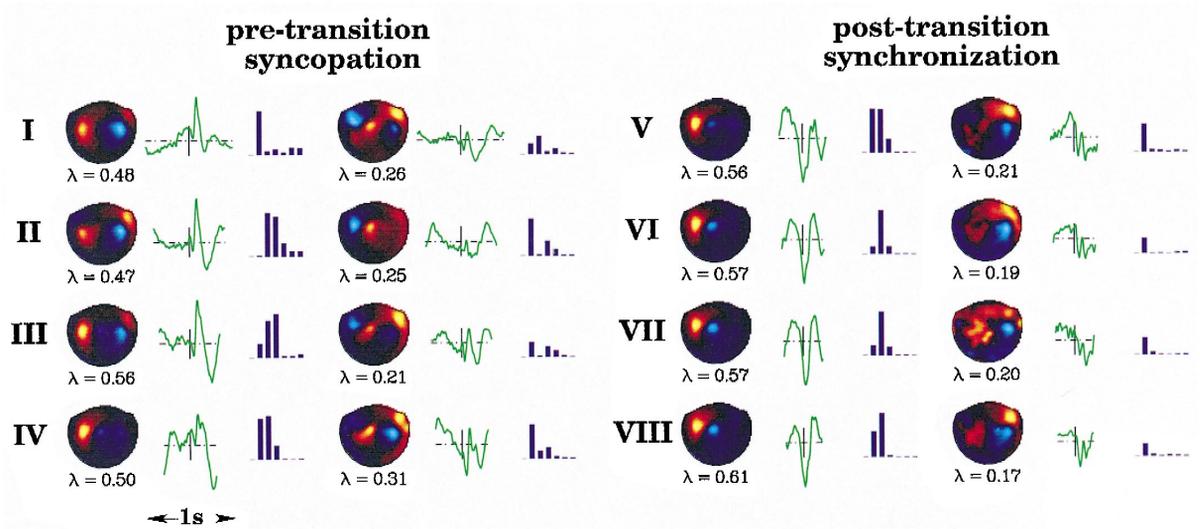
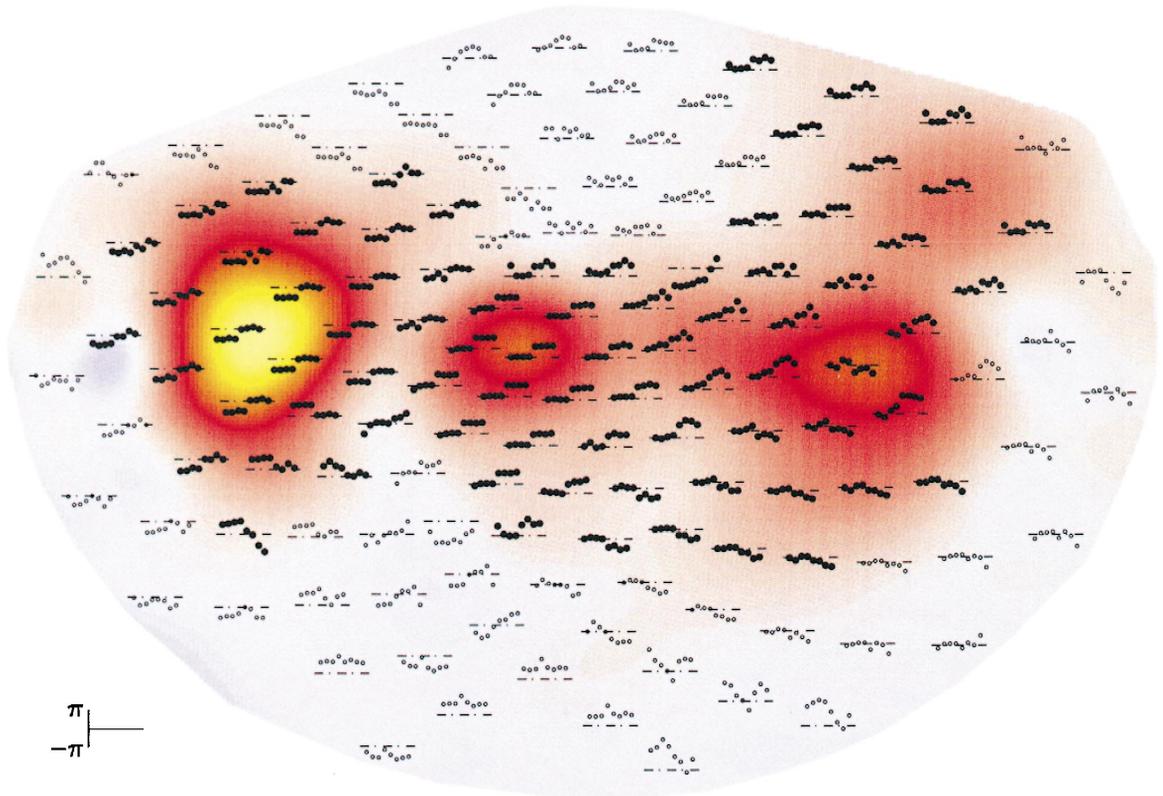


Fig. 2. (Top) Relative phase between the stimulus and the brain signal for the syncopate condition on all eight plateaus underlaid with the spatial patterns representing the power of the largest Fourier component at the coordination frequency. Larger solid circles indicate that the power at the coordination frequency in this channel was larger than 5% of the largest power on at least one plateau. Smaller open circles were used when the largest power did not exceed this value. Fig. 5: (Bottom) The first two modes and their time-dependent amplitudes and spectra from a principal component analysis of the syncopation condition on all frequency plateaus.

Fig. 4 shows the phase of the first Fourier component from the spectra calculated as the inverse tangent of the ratio between the imaginary and real part. We find a jump in the phase by a value of  $\pi$  in certain areas that parallels the transition in the coordination behavior. Switching is most pronounced over left auditory and motor areas (where the amplitude of the signal is strong) whereas in other sensors, in particular occipital and frontal areas, the phase is not well defined and the amplitude of the signal is very small. Notice that over motor cortex the phase changes from  $-\pi$  to 0 in the left part of the dipole and from 0 to  $\pi$  in the right half due to the different polarity of the dipolar pattern.

Fig. 5 shows the result of a principal component analysis of our data set on all frequency plateaus, i.e. the two dominating spatial patterns, their time dependent amplitude and the first six components of the power spectrum. Pre-transition the shape of the dominant pattern is similar to an auditory evoked field with the second pattern carrying more of the motor component. Post-transition this situation is reversed. Moreover, the time series of the dominant pattern post-transition obviously oscillates at double the coordination frequency.

#### 4. Comparing results

Unfortunately, DPB do not provide a plot of their averaged time series in single channels in the Letter (c.f. our Fig. 2). Therefore, the first figure that can be compared is the plot of phases, their Fig. 2 and our Fig. 4. It is surprising that they find very clean transitions in so many sensors. Even more puzzling is where these sensors are located, i.e. in occipital and frontal areas and in the left and right boundaries of the sensor array. Over the contralateral motor area where the signal should be strong and clean (as in our data), their curves are very noisy and, as indicated by the error bars in their Fig. 2, this region also exhibits the largest variance in the phase.

Figs. 3 and 5 in DPB show plots of a principal component analysis of the MEG data set over the whole experiment and separately on single frequency plateaus, respectively. The spatial shape of these patterns is not what one would expect from the literature on evoked auditory and motor fields [2,6,15]

and contrasts with our Fig. 5 where the dominating activity switches from an auditory-like pattern (pre-transition) to a movement-like pattern (post-transition). In particular, the strong occipital activity seen in the modes shown in their Fig. 5 is peculiar but may serve as a clue for an explanation of these differences. Finally, Fig. 6 in DPB points to differences between the power spectra of averaged time series and the average over the spectra taken from the raw signals. It is well-known that these are not the same. However, as our interest is with respect to time-locked events, the way to average the signals for our purpose is in the time domain.

#### 5. Discussing the differences

Comparing the figures in DPB and those shown here it is quite obvious that there are a number of discrepancies even beyond what Daffertshofer et al. describe. A key may lie in the strong occipital activity that can be seen in Fig. 5 of DPB. In their experiment the subject had her eyes closed (a quite unusual setup because of the lengthy trail runs in this type of experiment) which is well known to trigger strong alpha activity. Even though the data were filtered in a range 0.1–7 Hz the only explanation we can think of for the strong occipital activity in DPB is to see it as remnant of large amplitude alpha activity. That is to say, although filtering may remove a frequency band from the data, differences in the subjects' sensory experience between their study (eyes closed) and ours (eyes open) cannot be removed or easily discounted. Moreover, in an essentially nonlinear coupled system like the human brain, simply filtering out a frequency band does not remove the influence of that activity on other frequencies.

In summary, we appreciate very much the efforts DPB have made to replicate the original experiment published in this Journal. They are one of only a few groups to study the mechanisms underlying switching in the brain by systematically manipulating system-sensitive control parameters. Nevertheless, some of the foregoing findings and considerations presented here render a full comparison with DPB's work difficult. Most telling, perhaps, are the time series shown here in Figs. 2 and 5 which appear to

counter, if not question the value of, speculations about whether a certain frequency component is artifactual or not.

### Acknowledgements

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