PHASE-ORDERED EEG PATTERNS APPEAR DURING ANTICIPATION OF OMITTED STIMULI – NOT ONLY IN THE ALPHA-RANGE

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Abstract

The experiments of the present study were designed to explore the phase reordering of oscillations in EEG frequency bands as a function of stimulus-onset asynchrony (SOA) in an omitted-stimulus anticipation paradigm. Phase ordering at around the anticipated point of time has been previously reported for periodically presented auditory and visual stimuli, and SOAs fixed at one value (Maltseva et al., 2000). Results indicate that phase reordering in the EEG alpha band accompanies timing activity of subjects and reflects brain dynamics involved in cognitive processing. In the present study, as in the previous one, subjects were instructed to anticipate omitted stimuli and to mark the time of anticipated onset either mentally or by pressing a button. After a series of pure listening, a series with button pressing was performed between two series with mental marking. Each session contained 4 experimental blocks with different SOAs. EEG was obtained from 19 sites in frontal, central, temporal, parietal and occipital areas. Correlation analysis of sweeps for each individual revealed similar phase reordering of oscillations in the theta, alpha, beta and gamma EEG bands. These patterns of phase-ordered activity appeared during mental marking of omitted stimuli in all subjects and at all sites, however, to different degrees and rarely simultaneously in all bands.

A major goal of brain research is to detect regularities in the brain's electrical activity during sensory-cognitive information processing. One tool to attain this goal is event-related brain potentials which reflect the summated time courses of underlying neural oscillations in different frequency ranges. Alternatively, effects of information processing upon brain activity can be assessed by directly referring to oscillatory components in the frequency or real-time domains. As many findings indicate, theta, alpha, and gamma band activities are functionally relevant to information processing, and phase reordering in different EEG ranges is sensitive to processing task (Maltseva, Geissler, Başar 2000; Yordanowa, Kolev, Demiralp 1997; Kolev, Yordanowa, Schürmann, Başar 1999).

In the present paper, an investigation into phase reordering of oscillations in the EEG is reported in which a technique of real-time analysis was applied to sets of single sweeps as data basis. An important property of phase relations between sweeps within and between recording trials is that they may occur irrespective of amplitude differences.

The following experiment is based upon a study of Maltseva et al. (2000), in which systematic phase reordering in the EEG alpha-range for mental marking of omitted stimuli has been demonstrated. Specifically, it was shown that during reproduction of stimulus-onset asynchronies (SOAs) in anticipating omitted stimuli alpha oscillations become locked to the moment of subjective representation of the omitted stimulus.

The main hypothesis of the present analysis is that such phase-ordered patterns occur in other frequency bands, too. To check this hypothesis, besides task, SOAs were varied. EEG records were analyzed in the theta, alpha, beta, and gamma ranges.

Method

Subjects

Seven healthy adults (three females) from 20 to 44 years of age were assessed. They were right-handed and without any history of neurologic, psychiatric disorders or hearing problems. Subjects were seated in a soundproof and dimly illuminated room with eyes open.

Stimuli

The auditory stimuli were 1000 Hz tones with intensity of 65 dB SPL, duration of 200 msec (r/f 20 msec). The tones were presented regularly with stimulus-onset asynchronies of 845, 1690, 2535, and 3380 msec, respectively. Each series contained 112 tones, every fourth signal was omitted.

Task

Subjects were instructed to anticipate omitted stimuli and to mark the onset time either mentally or by pressing a button. A series with button pressing was performed between two series with mental marking. Each session contained 4 experimental blocks with increasing SOA. Prior to all blocks there was a listening series, where the task for the subjects was to listen to the stimuli and not to think about the task.

Data acquisition

EEG data were recorded continuously at Fz, Cz, Pz, FP1, FP2, F7, F8, F3, F4, T3, T4, C3, C4, P3, P4, O1, O2, left and right mastoids with nose as the reference using a .3-200 Hz bandpass, with a sampling frequency of 1000 Hz. The ground electrode was positioned on the forehead. The electro-oculogram (EOG) was recorded bipolary from above and below the left eye and the outer canthus of each eye. Electrode impedance was kept below 5 kΩ. EEG segments contaminated with ocular or muscular activity, or exceeding ± 50 μV, were excluded from further analysis.

Data analysis

For determination of phase-ordered patterns all artifact-free sweeps in the interval of the first, second, third, and fourth (omitted) stimulus were assigned to four groups of 10 neighboring sweeps (only 10, because of subjects changing strategies over the series), for example, when all sweeps were artifact-free, groups consisted of sweeps numbered 1-10, 7-16, 13-22, 19-28. These sweeps of each series and each channel were digitally filtered in the theta (5 Hz – 8 Hz), alpha (8 Hz –13 Hz), beta (13 Hz – 30 Hz), gamma1 (30 Hz – 48 Hz) and gamma2 (52 Hz – 90 Hz) ranges. Some of the superimposed filtered sweeps show phase-ordered patterns (Figure 1). One major problem in quantifying this phase alignment arises from the fact that the traditional methods such as averaging and power spectral density functions are not suitable, since there are only ten sweeps and phase reordering is often not combined with an increase in amplitude. Therefore, for each group and each electrode Pearson correlation coefficients were computed for each pairwise combination of the 10 sweeps within a frequency-dependent window (theta: 240 msec, alpha: 150 msec, beta: 75 msec, gamma1: 40 msec, gamma2: 25 msec) which was shifted along the time axis in steps of the time window (theta: 80 msec, alpha: 50 msec, beta: 25 msec, gamma1: 13 msec, gamma2: 8 msec). This correlation coefficient increases when the two sweeps get phasealigned. For further analysis, a set of 19 900 correlation coefficients was calculated from 200 appropriate time windows which were taken for each individual from a series with SOA = 3380 msec in an epoch of -1000 to +1000 msec around omitted stimuli. By means of the U-test of Mann and Whitney (Krause, Metzler 1988) we computed a criterion for the estimation of significance of the 45 correlation coefficients compared with the whole set. The resulting z-values were standard normalized ($p < .05$: z-value > 1.96; $p < .01$: z-value >2.58).

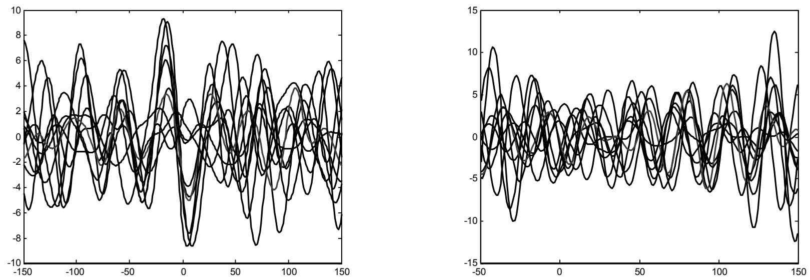
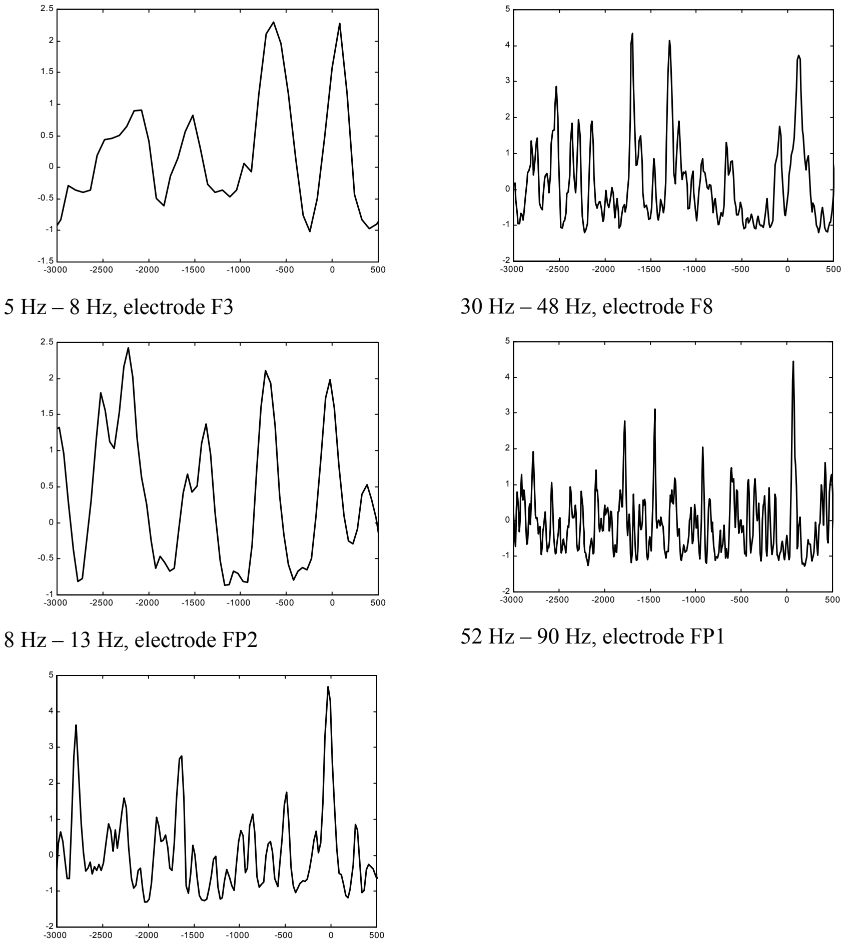


Fig. 1. Superimposed sweeps. Subject RK, SOA = 845 msec, electrode F8, omitted stimulus is at time 0 msec. **Left:** sweeps filtered in the beta range; increased phase alignment in the interval [-20 msec, 20 msec]. **Right:** sweeps filtered in the gamma1 range; increased phase alignment in the interval [80 msec, 110 msec].

Results and Discussion

Phase-ordered patterns appearing during anticipation of omitted stimuli could be shown for all stimulus-onset asynchronies, for all subjects and, in patterns varying between conditions, for all electrodes and all frequency bands. However, the distribution of significance of z-values is closely related to attention and to the accuracy of the performance of the subjects. Strong individual differences were found and thus the following figures represent only a small but interesting fraction of the whole set of the z-value courses.

Figures 2 and 3 present two examples of phase-ordered patterns for SOA = 845 msec and for SOA = 2535 msec. The five curves illustrate the variation of z-values in the theta, alpha, beta, gamma1 and gamma2 ranges for the epoch of the first, second, third and the omitted, fourth, stimulus. For the shortest SOA, as illustrated, there are phase-ordered patterns in the time around 0 msec in all five frequency bands. These z-values are significant ($p<.05$) simultaneously for up to 9 electrodes, but there are no electrodes with significant values in all bands (as in Figure 3). The z-values in the theta and in the alpha range show the influence of all four stimuli. This pattern was found throughout all areas but with different z-values. There are electrodes with a maximum effect of the first or of the third or of the omitted stimulus. In the case of Figure 3 only theta, alpha and beta responses occur as a function of stimulation. They were computed for 28 sweeps, because of the high stability of this series. In the theta range the peak for the first stimulus occurs simultaneously at 10 electrodes at time -7440 msec (165 msec after the stimulus), the second in 17 electrodes at time -4880 msec (190 msec after the stimulus) and the third in 15 electrodes at time -2400 msec and -2320 msec (approximate 175 msec after the stimulus). In the alpha range the first peak occurs in 7 electrodes at -7525 msec (80 msec after the stimulus), the second in 8 electrodes at -4925 msec (145 msec after the stimulus), the third is not significant and the fourth peak occurs simultaneous in 17 electrodes at time -725 msec and in 14 electrodes at -125 msec. The two highest peaks in the beta range occur at -987 msec (8 electrodes) and at 63 msec (6 electrodes). The z-values for the gamma1 and gamma2 ranges are frequently significant, too, but no connection to the stimuli is evident.



5 Hz – 8 Hz, electrode F3

30 Hz – 48 Hz, electrode F8

8 Hz – 13 Hz, electrode FP2

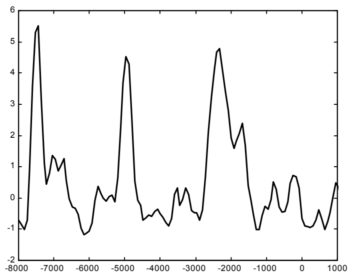
52 Hz – 90 Hz, electrode FP1

13 Hz – 30 Hz, electrode F8

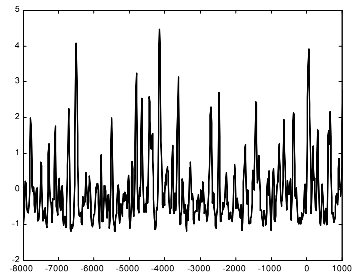
Fig. 2. z-values of 10 sweeps for SOA = 845 msec, subject RK. First stimulus is at -2535 msec, second at -1690 msec, third at -845 msec and omitted stimulus at 0 msec.

To summarize, there are phase-ordered patterns appearing during anticipation of omitted stimuli in the theta, alpha, beta and, partially, in the gamma EEG bands. In these two series, the same pattern was also found for the presented stimuli. There is generally no proof of preference of some electrodes.

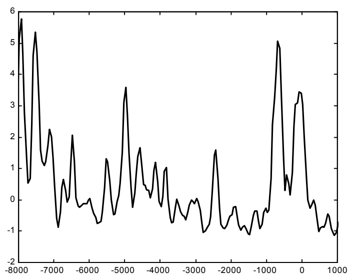
It appears that the shortest stimulus-onset asynchronies induce phase reordering not only in the alpha range.



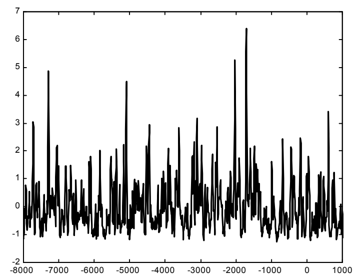
5 Hz – 8 Hz, electrode FP2



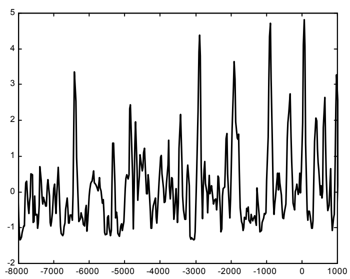
30 Hz – 48 Hz, electrode FP2



8 Hz – 13 Hz, electrode FP2



52 Hz – 90 Hz, electrode FP2



13 Hz – 30 Hz, electrode FP2

Fig. 3. z-values of 28 sweeps for SOA = 2535 msec, subject RK. First stimulus is at -7605 msec, second at -5070 msec, third at -2535 msec and omitted stimulus at 0 msec.

The courses for SOA = 2535 msec often show a peak for omitted stimuli in front of the main peak. We do not want to speculate here on this interesting phenomenon.

Taken together, the findings reported throw doubt upon any explanations of temporal anticipation performance solely in terms of alpha activity (cf. Maltseva et al., 2000), but even an approach as that of Geissler (1997), which leads to the expectation that other bands may be involved, have not yet been sufficiently elaborated to explain the pattern of results observed.

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