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Induced alpha band power changes in the human EEG and attention

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Abstract

Induced alpha power (in a lower, intermediate and upper band) which is deprived from evoked electroencephalograph (EEG) activity was analyzed in an oddball task in which a warning signal (WS) preceded a target or non-target. The lower band, reflecting phasic alertness, desynchronizes only in response to the WS and target. The intermediate band, reflecting expectancy, desynchronizes about 1 s before a target or non-target appears. Upper alpha desynchronizes only after a target is presented and, thus, reflects the performance of the task which was to count the targets. Thus, only slower alpha frequencies reflect attentional demands such as alertness and expectancy. © 1998 Elsevier Science Ireland Ltd.

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Alpha desynchronization (suppression) is probably the best known electroencephalographic (EEG) phenomenon [1]. Since the early days of EEG research it was suggested that alpha suppression reflects attentional processes [11,15]. However, more recent evidence indicates that different frequency bands within the extended alpha frequency range reflect quite different cognitive processes [5]. In a series of experiments we were able to show that upper alpha desynchronization (in the range of about 10.5–12.5 Hz) is selectively associated with the processing of sensory-semantic information [6] whereas desynchronization in the broad range of about 6.5–10.5 Hz reflects attentional processes [5,8].

The purpose of the present study is two-fold. First, we want to extend the hypothesis about the relationship between lower alpha desynchronization and attention by testing the proposal that within the broad range of about 6.5–10.5 Hz subbands of 2 Hz can be distinguished that reflect different components of attention. Second, because it is well known that a variety of different components of event-related potentials (ERP's) are sensitive to attentional demands, we want to show whether event-related band power changes that can be observed in response to attentional demands are due to ERP components. Thereby, we measure changes in induced band power (IBP) which are deprived from evoked EEG activity [4,9].

The use of narrow frequency bands particularly in the lower alpha frequency range bears the danger that theta synchronization counteracts with alpha desynchronization if frequency bands are not adjusted individually for each subject. This fact is demonstrated by the two power spectra in Fig. 1A which represent a resting (dotted line) and a test condition (bold line). In a test condition in which a subject has to perform some kind of task, alpha desynchronizes [12] but theta synchronizes [8,10]. Thus, as Fig. 1A demonstrates, at a certain frequency which is termed 'transition frequency' (TF) theta synchronization gives way to alpha desynchronization. In a recent study [7] we have found that Spearman's rank correlation between the individually determined alpha frequency (IAF) and TF yielded a significant value of $\rho = 0.64$ (one sided: $P < 0.02$; two sided: $P < 0.04$). Similar results were reported by Doppelmayr et al. [3]. These findings document that theta varies as a function of alpha frequency and suggest to use alpha frequency as a common reference point for adjusting different frequency bands. Particularly for the lower alpha band the individual determination of frequency bands is of crucial importance

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because otherwise the effects of alpha desynchronization are masked by theta synchronization. In several independent studies [6,7,9] we have found that TF lies about 4 Hz below IAF. Accordingly we use two lower alpha bands. Lower-1 alpha lies in the range of IAF –4 Hz to IAF –2 Hz whereas the intermediate or lower-2 alpha band falls below IAF (IAF-2 Hz to IAF).

Cognitive theories distinguish between different components of attention [13,14]. As an example, Posner [13] considers alertness (a concept similar to arousal) an important component of attention. Alertness is further subdivided into phasic and tonic alertness. Phasic changes in alertness occur at a rapid rate and are under volitional control whereas tonic changes occur at a much slower rate and are not under direct volitional control. A good example of a phasic change is the increase in alertness after the presentation of a warning signal.

The effects of phasic alertness and expectancy (as a special form of selective attention [13]) can be studied by using a modified oddball task in which a warning signal (WS) precedes the presentation of an imperative stimulus (target or non-target). Subjects have the task to count the targets but to ignore non-targets. We assume that the warning signal and the target increase alertness and that the time before a target or non-target appears reflects a state of increased expectancy (cf. Fig. 1B,C). The presentation of targets and non-targets was not completely random. On the one hand, targets are rare and non-targets are frequent (the ratio is 30:70%) and on the other hand, no more than three targets or non-targets were allowed to occur in succession. Thus, on the average, subjects were well able to expect (and make a good guess about) the occurrence of a target after a few trials. A large number of trials (200 stimulus presentations) was used to guarantee that subjects have enough time to get familiar with the sequence of targets and non-targets.

The EEG was recorded while 14 right handed volunteers (five male and nine female students, mean age 24 years with a range of 19–31 years) performed a modified visual oddball paradigm. A set of 60 targets (a row of five X's: XXXXX) and 140 non-targets (five O's: OOOOO) was used. Subjects were asked to silently count the targets and to press a response key with the right index finger. Non-targets had to be ignored.

The length of a single trial (epoch) was 7 s. A brief warning signal (3000 Hz, lasting for 250 ms) was presented 1250 ms before a target or non-target appeared at 2750 ms after the beginning of each trial. Targets and non-targets appeared at the center of a computer monitor for 1000 ms. They were 0.7 cm in height and 3 cm in length. Subjects sat at a distance of 90 cm from the monitor.

In addition to electrodes placed at F3, F4, Cz, Pz, O1 and O2, two electrodes were attached to the left and right ear lobe and the EOG was recorded from two pairs of leads to register eye movements. All data were recorded referentially against a common reference placed on the nose with re-referencing against averaged ear lobes (for details see [6, 7]). EEG-signals were amplified by a biosignal amplifier system (frequency response: 0.16–30 Hz), subjected to an anti-aliasing filterbank (cut-off frequency: 30 Hz, 110 dB/ octave) and were then converted to a digital format (sampling rate: 128 Hz).

After rejecting artifacts (eye blinks, eye movements, muscle artifacts, etc.) by visual inspection, and the few erroneous trials (less than 1%) an average of 45 epochs remained for the targets and 96 for the non-targets, respectively.

The frequency windows for a lower, intermediate (also termed lower-1 and lower-2 alpha) and upper alpha band

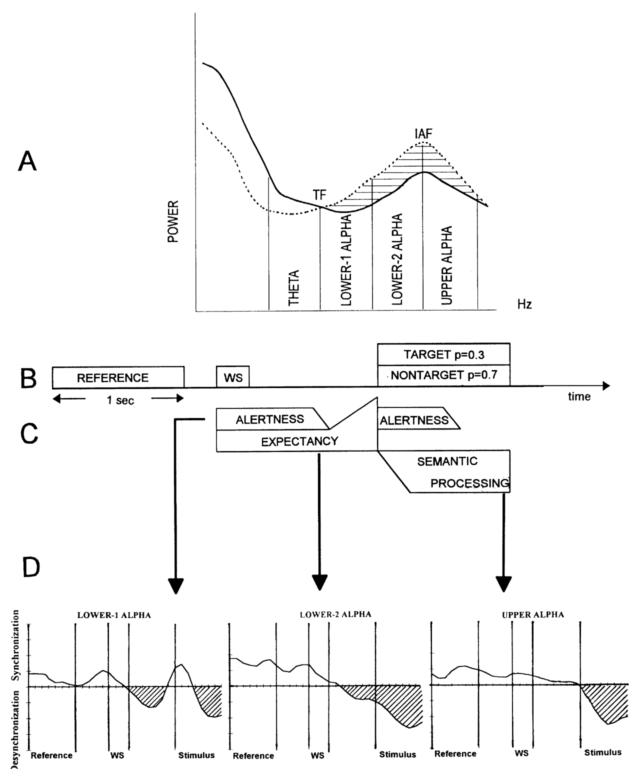

Fig. 1. (A) In response to task demands (bold line) and in comparison to a resting or reference interval (dotted line) alpha desynchronizes but theta synchronizes. That frequency where theta synchronization gives way to alpha desynchronization is termed 'transition frequency' or TF. Experimental data show that the individual alpha frequency (IAF) is correlated with TF and proved useful to serve as cut off point between individually determined lower and upper alpha bands. In easy tasks, such as in the oddball task of our study, changes in IAF between the reference and task period usually are negligible. (B) The structure of a single trial in the modified oddball task where an alerting warning signal precedes a to be an attended target or a to be ignored non-target. (C) The assumed sequence of cognitive operations. (D) The expected results for targets, schematically drawn. It is assumed that the lower-1 alpha band reflects phasic alertness and responds to the WS and imperative stimulus with a decrease in band power (desynchronization, shaded area). The lower-2 alpha band reflects expectancy and desynchronizes before the imperative stimulus appears. The upper alpha band reflects semantic processes that are related to task performance and, thus, shows maximal desynchronization in the late poststimulus interval (for targets) only.

were determined individually for each subject by using IAF (calculated for the entire epoch and averaged over all epochs and leads) as an anchor point (cf. Fig. 1A; for details see [6, 7,9]). Averaged over the sample of subjects the three alpha bands lie in the following frequency ranges: 6.4–8.4 Hz, 8.4–10.4 Hz and 10.4–12.4 Hz.

For each of the three alpha bands IBP was calculated by using a recently developed method [9] which is based on the assumption of a linear superposition of the poststimulus EEG and the ERP. For each sample point i of the band pass filtered data $x(i,j)$, the mean $\mu(i)$, representing the filtered ERP, is calculated over the $j = 1.....n$ epochs for each electrode site, experimental condition (target, non-target) and subject. Then, the differences between the filtered data $x(i,j)$ and the mean $\mu(i)$ are squared: $x'(i,j) = [x(i,j) - \mu(i)]^2$. After averaging within consecutive time windows of 125 ms and over the $j = 1.....n$ epochs, z-values were computed for each subject, recording site and experimental condition. The z-transformed power values are termed IBP.

The significance of changes in band power in response to the presentation of a stimulus with respect to a reference

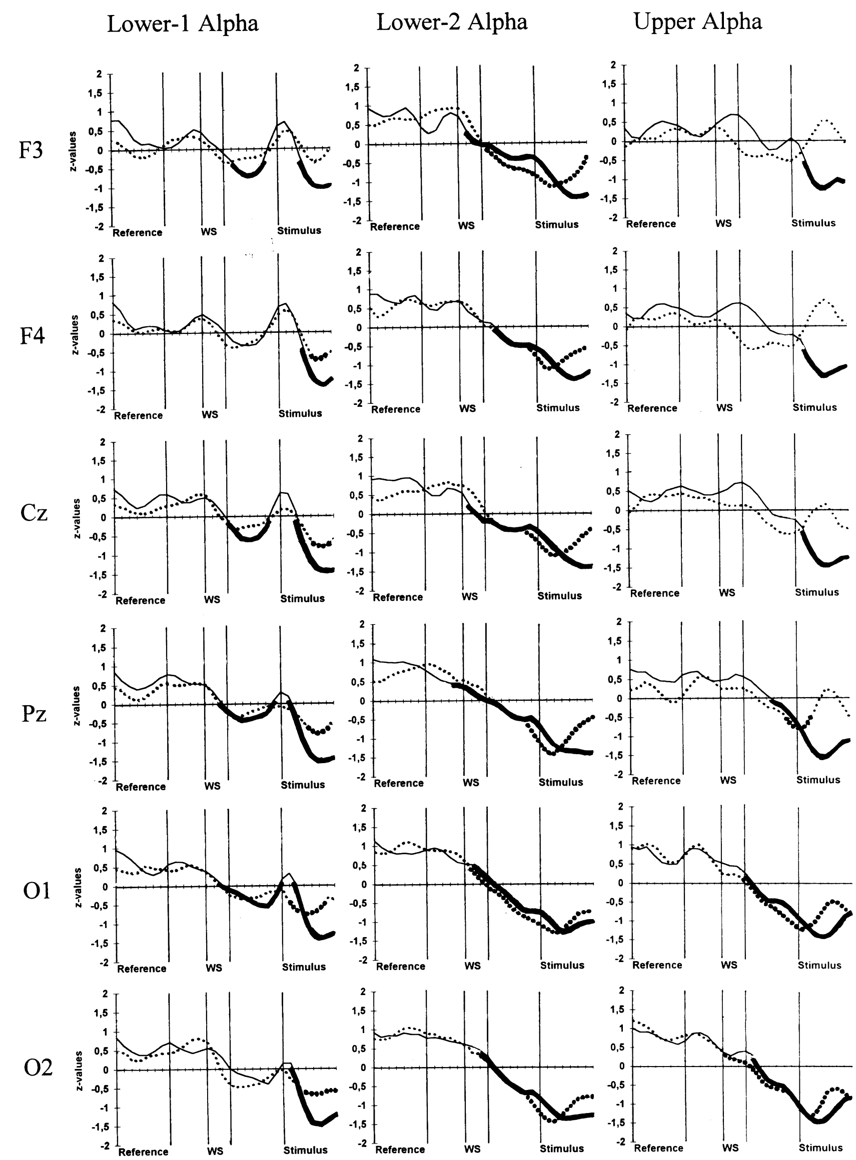

Fig. 2. Time course of changes in induced band power (IBP) for targets (bold line) and non-targets (dashed line) in three alpha frequency bands with a width of 2 Hz each. IBP represents z-transformed power. The reference interval was used to calculate confidence intervals. Thus, significant changes (marked by extra bold segments) refer to differences between the reference interval and subsequent time periods. Note that the reference intervals and the respective standard deviation for targets and non-targets may differ. As a consequence, confidence intervals are also different between targets and non-targets. The lower-1 alpha band shows a phasic response to the WS and imperative stimulus, whereas the lower-2 alpha band exhibits a tonic increase in desynchronization (reflected by negative z-values) that starts already before a target and non-target appears. The upper alpha band shows the largest difference between targets and non-targets. Maximal desynchronization occurs in the poststimulus period for targets only.

period (represented by the first 1000 ms of an epoch) was evaluated on the basis of 99.9% confidence intervals [9]. Confidence intervals were calculated separately for targets and non-targets and for each recording site.

The time course of IBP changes is depicted in Fig. 2. Those parts of IBP which fall outside the 99.9% confidence intervals are marked by extra bold lines. In general, targets show a larger extent of desynchronization (negative *z*-values) than non-targets. In the lower-1 alpha band the warning signal (WS) preceding a target induces a significant desynchronization which is distinct from the desynchronization that is induced by the appearance of a target. In contrast, the lower-2 alpha band responds with a steady (tonic) increase in desynchronization starting after WS. For non-targets maximal desynchronization is reached during stimulus onset whereas for targets maximal desynchronization is reached about 500 ms poststimulus. Most interestingly, at F3, F4 and Cz, a significant upper alpha desynchronization occurs in the poststimulus interval for targets only.

The results demonstrate that a significant response (decrease in band power) to the warning signal can be observed only in the lower-1 alpha band and when the warning signal preceded a target. This finding indicates that, on average, subjects were able to predict (expect) the occurrence of a target and that the warning signal exerts an alerting effect primarily if it precedes a target. This alerting effect is reflected by a decrease in band power that is interrupted and, thus, separable from the decrease in band power that occurs in response to the imperative stimulus.

A tonic response (i.e. a steady decrease in band power starting as early as 1000 ms before the onset of an imperative stimulus), probably reflecting expectancy, was obtained in the lower-2 alpha band. Because expectancy plays a role during the prestimulus period of both types of stimuli, there is no reason to assume that the prestimulus period will differ between target and non-target trials (cf. Fig. 2). After the appearance of the imperative stimulus, however, the processing of targets and non-targets will be different. If a target appeared subjects expect still to perform another task which is to count and press the response key. Thus, during the poststimulus targets show a somewhat larger lower-2 alpha desynchronization than non-targets.

Because we have assumed that the upper alpha band reflects task specific effects, the largest differences between targets and non-targets are to be expected for the second half of the poststimulus interval (i.e. during the time the stimulus type is recognized and subjects start to count). This indeed is the case as Fig. 2 indicates (compare targets and non-targets in the upper and lower-2 alpha band particularly at F3, F4 and Cz).

The findings demonstrate that the distinction of three alpha bands proved useful for a better distinction of different cognitive processes. Because IBP is deprived from phase locked EEG activity, our findings are not due to or distorted by the influence of ERP's. We assume that IBP reflects induced oscillations that are modulated by stimuli or events and which (in contrast to evoked rhythms) do not respond in a phase locked manner (for a similar definition see [2]).

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