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Individual differences in brain dynamics: important implications for the calculation of event-related band power

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Abstract. Measures of event-related band power such as event-related desynchronization (ERD) are conventionally analyzed within fixed frequency bands, although it is known that EEG frequency varies as a function of a variety of factors. The question of how to determine these frequency bands for ERD analyses is discussed and a new method is proposed. The rationale of this new method is to adjust the frequency bands to the individual alpha frequency (IAF) for each subject and to determine the bandwidth for the alpha and theta bands as a percentage of IAF. As an example, if IAF equals 12 Hz, the widths of the alpha and theta bands are larger as compared to a subject with an IAF of, e.g., only 8 Hz. The results of an oddball paradigm show that the proposed method is superior to methods that are based on fixed frequencies and fixed bandwidths.

1 Introduction

Although it is well known that alpha (the dominant EEG frequency) varies as a function of age, EEG frequencies are conventionally subdivided into fixed frequency bands such as theta (4–8 Hz), alpha (8–13 Hz), beta (14–30 Hz), and gamma (30–70 Hz). From childhood to puberty the mean EEG frequency increases with age (Epstein 1980), but then decreases for the remaining life span. After puberty the alpha frequency starts to decline with increasing age. As an example, Köpruner et al. (1984) have found a linear relationship within the age range of adult subjects. They have shown that a young adult of, for example, 20 years has an expected alpha frequency of about 11 Hz, whereas a 70-year old subject shows a drop of 2.65 Hz down to a frequency of 8.24 Hz. In addition, data from our laboratory have indicated that even subjects of the same age show a considerable variability in alpha frequency, with a mean standard deviation of about 1 Hz (e.g., the reviews in Klimesch 1996, 1997). This means that even for age-matched subjects, an interindividual difference of about 2 Hz is quite a common case. Klimesch et al. (1990, 1993) have found evidence that these interindividual differences in alpha frequency are largely due to interindividual differences in memory performance.

Because of this large interindividual variability in alpha frequency, significant portions of alpha power will fall outside a fixed frequency window when event-related desynchronization (ERD), a method originally proposed by Pfurtscheller and Aranibar (1977), or other types of band power measures are calculated. As an example, let us consider a subject with a low alpha frequency and let us assume that the lower alpha band falls below the frequency window of the fixed band, which then covers only the upper alpha and some portions of the lower beta bands. In this case, event-related changes in the lower alpha band cannot be detected and changes in the upper alpha band will be misinterpreted if a fixed band is used. This example demonstrates that frequency bands should be adjusted individually for each subject. One method that was applied in earlier studies (Klimesch et al. 1996a, 1996b, 1997a) in our laboratory was to use the individual alpha frequency (IAF) as an anchor point for distinguishing a lower from an upper alpha band. Although this method proved superior to the use of fixed frequency bands (Schimke et al. 1990), the question still is whether the bandwidth may be considered a constant value that does not vary as a function of IAF. Before we consider this question in more detail, we want to show that besides the variation in IAF, the strikingly different reactions of the lower and upper alpha bands and the transition from alpha desynchronization to theta synchronization provide additional arguments for an individual adjustment of frequency bands.

The results from principal component analyses have repeatedly shown that power values in the alpha band load on two different and orthogonal components, with highest loadings in the lower and upper alpha bands. As an example, Mecklinger et al. (1992) found two orthogonal components, one with highest loadings between 7 and 11 Hz and a second with highest loadings

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between 10 and 13 Hz. These data indicate that power values of the lower and upper alpha bands vary largely independently of each other. Experiments from our laboratory have shown that lower alpha ERD varies as a function of attentional demands whereas upper alpha ERD is associated with (semantic) memory demands (Klimesch 1996, 1997). Thus, the use of individually adjusted frequency bands is essential to prevent task-related band power changes in the lower and upper alpha bands overlapping and cancelling each other.

Another important finding that questions the use of fixed frequency bands is based on the fact that, with increasing task demands, alpha desynchronizes whereas theta synchronizes (see the reviews in Schacter 1977 and Klimesch 1996). These opposite changes in theta and alpha band power can be observed if a reference condition in which subjects are in a state of alert wakefulness is compared with a test condition in which the subjects perform some type of task. In a recent study (Klimesch et al. 1996a) we were able to demonstrate that the transition between alpha desynchronization and theta synchronization occurs within a narrow frequency range that varies as a function of IAF. This frequency, where theta synchronization gives way to alpha desynchronization, is called the transition frequency (TF). Consequently, if rather broad frequency bands are used which are not adjusted to IAF, these effects of an event-related increase (synchronization) and decrease (desynchronization) in band power will tend to cancel each other.

It is the purpose of the present paper to show the usefulness of a new method for determining frequency bands as well as the bandwidth individually for each subject. It is proposed to use IAF as cut-off frequency between the lower and upper alpha bands and to use a percentage of IAF to determine the width of frequency bands. When attempting to determine the bandwidth individually, the crucial question is: What criterion should be used? We proceed from the idea that TF marks the cut-off frequency between the theta and lower alpha bands. In previous research we have found that TF lies at about 4 Hz below IAF and is significantly correlated with IAF (cf. Klimesch et al. 1996a). It should be noted, however, that TF shows a variation of about ± 0.5 Hz between different studies. In tasks where theta synchronization dominates, TF lies somewhat higher (at about 3.5 Hz below IAF) as compared to tasks where alpha desynchronization dominates. In the latter case, TF may be on average as low as about 4.5 Hz below IAF. Because a mean bandwidth of 4 Hz proved useful in previous studies, we suggest to uses steps of 20% IAF for an individual determination of the bandwidth. As an example, a subject with IAF $=$ 10 Hz would be expected to show an individual bandwidth of 2×2 Hz for the lower alpha band. We have found (e.g., Klimesch et al. 1996a) that the width of the lower alpha band is about twice as wide as that of the upper band. Thus, for the analysis of ERD, we distinguish between three steps of 20% IAF, two steps below and 1 step above IAF. The two frequency bands below IAF are termed lower-1 and lower-2-alpha, respectively. Because we have found that the TF between alpha de- and theta synchronization lies at about 4 Hz below the IAF of about 10 Hz, and because TF and IAF are significantly correlated (cf. Klimesch et al. 1996a), we suggest to use steps of 20% IAF to cover the range of individual theta and alpha bands. Using individually determined frequency bands and bandwidths avoids a confusion between event-related changes in the lower and upper alpha band and prevents the desynchronizing and synchronizing responses of the alpha and theta bands cancelling each other.

In order to show that the proposed method, which uses individually defined bands and widths (IBIW), is indeed superior to a method using fixed bands and fixed widths (FBFW) and also superior to a method using individually adjusted bands but fixed widths (IBFW), control computations must be performed. For that purpose we use data from an oddball paradigm (in which subjects have to respond to rare target and ignore frequent nontarget stimuli) and distinguish two groups of subjects, one with high alpha frequency and another with low alpha frequency. Then, by applying the different methods for defining frequency bands and bandwidths, ERD is calculated for both groups of subjects.

One obvious criterion for considering the proposed method superior to FBFW and IBFW is that the two groups of subjects with low and high alpha frequency do not show significant differences when frequency bands are defined according to IBIW. Another criterion is based on physiological considerations and refers to that frequency band which is given by the difference between IAF and TF. Because TF defines the transition from the alpha to the theta band and because IAF defines the transition from the lower to the upper alpha band, the frequency window given by IAF $-$ TF equals the bandwidth of the lower alpha band. Thus, according to IBIW, the width of the lower alpha band IAF $-$ TF will always be equal to a certain percentage of IAF. To illustrate this idea, the three different types of relationships between IAF and TF (corresponding to FBFW, IBFW, and IBIW) are plotted in Fig. 1. The dashed horizontal line characterizes FBFW and shows that TF remains constant regardless of variations in IAF. The dotted line exemplifies IBFW and illustrates a case where TF always is a constant value below IAF (reflecting a fixed bandwidth). The bold line illustrates IBIW and shows that – as compared to IBFW – TF is smaller for large values of IAF but larger for small values of IAF. Thus, the criterion for accepting IBIW as the adequate way to determine frequency bands is that the experimentally obtained relationship between IAF and TF fits the regression line predicted for IBIW. If IBIW is superior to FBFW and IBFW, and if IAF $-$ TF is equal to the bandwidth of the lower alpha band and proportional to IAF, then a significant correlation between IAF $-$ TF versus IAF (including also a significant correlation between TF and IAF) will be expected. It should be noted that for both methods, IBIW and IBFW, a positive correlation between TF and IAF is expected. However, for IBFW this correlation is solely due to the variations in IAF. Thus, because the bandwidth IAF $-$ TF is a strictly constant value for IBFW, only for IBIW is a significant correlation between IAF $-$ TF and IAF predicted.

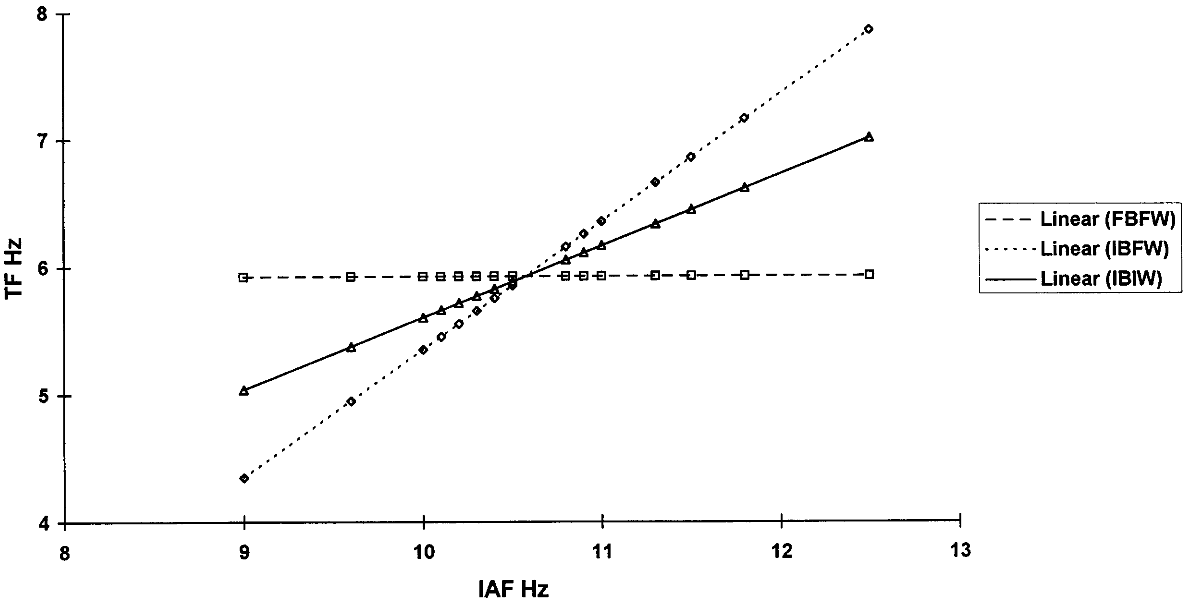

Fig. 1. Hypothetical regression lines between the individual alpha frequency (*IAF*) and the transition frequency (*TF*) of theta synchronization and alpha desynchronization for three different methods of frequency band definitions. While FBFW uses interindividually fixed frequency bands with a bandwidth of 2 Hz for each frequency, for IBFW and IBIW the bands are adjusted to IAF. Whereas IBFW uses a fixed width of 2 Hz, IBIW uses a percentage of 20% of the IAF as the width for the different frequency bands. The hypothetical line for FBFW is a horizontal line with *a* equal to mean TF (5.9 Hz in this study). For IBFW the mean difference between IAF and TF (i.e., 4.6 Hz) was subtracted from each value of IAF. The regression line for IBIW was computed by subtracting the mean difference (IAF − TF) as a percentage from IAF (i.e., 44%)

In order to avoid confusion it is important to note that in Fig. 1 the actual mean values for TF and IAF−TF which were found in the present study were used for plotting the regression lines. For FBFW the regression line lies at 5.9 Hz, which is the actual mean value of TF. The regression line for IBFW is based on the actual mean value of IAF−TF, which is 4.6 Hz or 44% and which is used for the regression line for IBIW. This was done to allow for a better comparison between the actual and predicted data.

The reason that all of the ERD analyses reported below are based on a bandwidth of 4 Hz (or 40%) for IAF−TF instead of the actual 4.6 Hz (or 44% respectively) is that TF varies between studies, depending on the specific task, and that a value of 4 Hz has proved useful in previous research. Thus, proceeding with a bandwidth of 4 Hz for IAF−TF allows for a better and easier comparison with results from previous studies as well as with data from other laboratories.

2 Method

2.1 Subjects

EEG data were recorded from 19 right-handed subjects (6 male and 13 female students) who participated voluntarily in the experiment. The mean age was 21.6 years (with a range of 20–31 years). Handedness was determined by asking subjects about the hand they use in ten different tasks such as handwriting, throwing a ball, etc. A subject was considered right-handed if he/she indicated to use the right hand for all of these different tasks and if none of the parents was left-handed.

2.2 Stimuli and procedure

A visual oddball paradigm was used in which targets and nontargets were presented randomly but with the restriction that no more than three targets or nontargets may occur in a row. A total of 200 stimuli were presented. Targets consisted of a row of five X's (XXXXX) and were presented at a probability of 0.30. Nontargets consisted of five O's (OOOOO) and were presented at a probability of 0.70. Subjects were instructed to press a response key with the right hand if a target occurs and to silently count the targets but to ignore nontargets. At the end of the experimental session, subjects had to report how many targets they had counted. The percentage of correct responses (pressing the response key) to targets was 99.2%.

Targets and nontargets appeared for 1 second at the center of a computer monitor (see Fig. 2). They were 0.7 cm in height and 3 cm in length. Subjects were placed at a distance of about 90 cm from the monitor in a comfortable armchair.

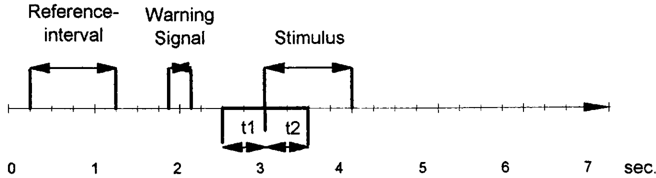

Fig. 2. A single trial comprises a total of 7 s and is composed of a reference interval (250–1250 ms), the presentation of a warning signal (1875–2125 ms), and an imperative stimulus (3000–4000 ms). The intervals t1 and t2 (500 ms duration each) mark the time intervals for which ERD was calculated

A brief acoustic warning signal (3000 Hz, lasting for 250 ms) appeared 1125 ms before a stimulus was presented. The length of a single trial was 7 s and the length of the whole session was 23 min and 20 s for each subject. In an attempt to avoid artifacts, subjects were asked to maintain fixation by looking at the middle of the screen and to prevent eyeblinking as soon as the warning signal appeared.

2.3 Recording and analysis of EEG data

EEG activity was recorded with a set of 12 silver electrodes (F3, F4, C3, Cz, C4, T3, T4, P3, Pz, P4, O1 and O2) according to the International Electrode (10–20) Placement system. For simplicity, only the data for Pz were analyzed. Furthermore, the electrooculogram (EOG) was recorded from two pairs of leads in order to record horizontal and vertical eye movements. All electrodes were attached with a Nihon Khoden glue paste to the scalp.

Data were recorded monopolarly against a common reference placed on the nose. In order to eliminate the effects of the nose reference as well as other types of artifacts, the EEG recordings were corrected by subtracting the arithmetically averaged ear recordings [(A1 + A2)/2] from all of the monopolar recordings.

EEG signals were amplified by a 32-channel biosignal amplifier system (frequency response: 0.16 to 30 Hz), subjected to an anti-aliasing filterbank (cut-off frequency: 30 Hz, 110 dB/octave) and were then converted to a digital format via a 32-channel A/D converter. Sampling rate was 128 Hz. During data acquisition, EEG signals were displayed online on a monitor and stored on disk for later analyses.

By visual inspection, all of the epochs were checked individually for artifacts (e.g., eye blinks, muscle artifacts). After rejecting artifacts, an average of 35 out of the 60 attended stimuli remained for further analyses; only targets were analyzed.

2.4 Calculation of ERD

ERD represents the percentage of a change in band power during a test interval with respect to a reference within a defined frequency band. When calculating ERD, in a first step the EEG data for each epoch and each channel are digitally band-pass filtered (in specific bands and with either fixed or varied bandwidths as described below in Sect. 2.5), squared (in order to obtain simple power estimates) and averaged separately for each experimental condition and for each subject. Based on these data, the percentage of event-related changes in band power are calculated in using the ERD procedure proposed by Pfurtscheller and Aranibar (1977), who have coined the term event-related desynchronization or ERD. Thus, ERD is defined as the percentage of decrease or increase in band power during a specific interval as compared to a reference interval: ERD% = {[(band power, reference interval) − (band power, test interval)]/(band power, reference interval)} $\times$ 100. For a more detailed description see, for example, Pfurtscheller and Klimesch (1992). It is important to note that positive values indicate a power suppression, while negative ERD values (also termed ERS for event-related synchronization, cf. Pfurtscheller 1992; Pfurtscheller et al. 1996) reflect an increase in power.

In the present study, an interval of 2750 to 1750 ms before the onset of the target was used as reference. Test intervals are the time periods of 500 ms preceding and following onset of the imperative stimulus. It is a well-established finding that during a variety of different tasks changes in band power can be observed with respect to a 'baseline' which usually is an interval preceding the onset of a task or stimulus by a few seconds (e.g., the reviews in Pfurtscheller 1992; Pfurtscheller and Klimesch 1992; Klimesch 1996).

2.5 The determination of frequency bands

Three different methods for determining the frequency windows were applied and according to this method, frequency windows for each of the delta, theta, lower-1-alpha, lower-2-alpha and upper-alpha bands were specified. Table 1 shows the mean frequency windows averaged over the entire sample of 19 subjects as well as the values for the subject with the highest and the lowest IAF.

2.5.1 Determination of FBFW

The frequency windows had a standard bandwidth of 2 Hz and were the same for all of the subjects. The delta band ranged from 2 to 4 Hz, the theta band from 4 to 6 Hz, the lower-1-alpha from 6 to 8 Hz, the lower-2-alpha from 8 to 10 Hz, and the upper-alpha band from 10 to 12 Hz.

2.5.2 Determination of IBFW

For each subject the peak frequency of the dominant EEG frequency in the alpha band for all recording sites was used as an anchor point. This mean IAF was calculated over the entire epoch of 7 s. Again, five different frequency bands with a bandwidth of 2 Hz each were defined by using IAF as the individual anchor point: (IAF-8) to (IAF-6), (IAF-6) to (IAF-4), (IAF-4) to (IAF-2), (IAF-2) to IAF, and IAF to (IAF + 2), termed delta, theta, lower-1-alpha, lower-2-alpha, and upper-alpha, respectively. Averaged over the entire sample of subjects, IAF was 10.6 Hz (see Table 1).

2.5.3 Determination of IBIW of EEG frequencies

As for IBFW, IAF was used as the cut-off frequency between the lower and upper alpha bands. However, the bandwidth was calculated as a percentage of the IAF:

Table 1 Frequency bands for three different methods of definition. The respective frequency values and the transition frequencies (*TFs*) are presented for the subject with the highest and the lowest individual alpha frequency (*IAF*) as well as for the mean of the whole 19 subject sample

		IAF	Delta		Theta		Lower-1-alpha		Lower-2-alpha		Upper-alpha		TF
			From	To	From	To	From	To	From	To	From	To	
FBFW	lowest IAF	9.0	2.0	4.0	4.0	6.0	6.0	8.0	8.0	10.0	10.0	12.0	4.3
	highest IAF	12.5	2.0	4.0	4.0	6.0	6.0	8.0	8.0	10.0	10.0	12.0	6.5
	IAF of 19 subs.	10.57	2.00	4.00	4.00	6.00	6.00	8.00	8.00	10.00	10.00	12.00	5.93
IBFW	lowest IAF	9.0	1.0	3.0	3.0	5.0	5.0	7.0	7.0	9.0	9.0	11.0	4.3
	highest IAF	12.5	4.5	6.5	6.5	8.5	8.5	10.5	10.5	12.5	12.5	14.5	6.5
	IAF of 19 subs.	10.57	2.57	4.57	4.57	6.57	6.57	8.57	8.57	10.57	10.57	12.57	5.93
IBIW	lowest IAF	9.0	1.8	3.6	3.6	5.4	5.4	7.2	7.2	9.0	9.0	10.8	4.3
	highest IAF	12.5	2.5	5.0	5.0	7.5	7.5	10.0	10.0	12.5	12.5	15.0	6.5
	IAF of 19 subs.	10.57	2.11	4.23	4.23	6.34	6.34	8.46	8.46	10.57	10.57	12.68	5.93

(IAF × 0.2) to (IAF × 0.4), (IAF × 0.4) to (IAF × 0.6), (IAF × 0.6) to (IAF × 0.8), (IAF × 0.8) to IAF, and IAF to (IAF × 1.2).

2.6 Determination of TF between synchronization and desynchronization

As suggested by Klimesch et al. (1996a), each individual TF was determined by comparing the power spectra for the reference and test intervals. First, power spectra for the reference and test intervals were calculated for each subject and averaged over all trials. Then, the frequency of the transition region between the theta and alpha bands was determined within a fixed frequency window of 4–10 Hz. This was done by determining that frequency for each subject where the lines of the two power spectra intersected. This point was used as the indicator for the TF between theta and alpha. The idea behind this simple procedure is that during the test interval and in comparison the reference interval alpha power decreases whereas the theta power increases. Table 1 indicates the mean TF as well as the TF values for the subject with the highest and the lowest IAF.

2.7 Statistical analyses

First, a correlation was calculated between IAF and TF; it should be noted that a positive coefficient simply would show that TF increases with increasing IAF. Thus, in a second step, the difference between TF and IAF (representing the bandwidth of the two lower alpha bands) was correlated with the IAF.

Three different predictions can be distinguished:

(1) If TF is a constant value, TF and IAF would be not significantly correlated; in this case, FBFW can be assumed.
(2) If TF is significantly correlated with IAF (cf. Fig. 1), IBFW or IBIW can be assumed.
(3) In order to distinguish between the latter two cases the bandwidth IAF−TF is correlated with IAF. Only if this correlation is positive can IBIW be assumed.

In order to compare the results of the three different methods for determining frequency bands, subjects with a high versus low IAF were distinguished. Group IAF− comprises 10 subjects (6 female, 4 male) falling below the median; group IAF+, on the other hand, included 9 subjects (7 female, 2 male) with an IAF above the median. For each of the five frequency bands (delta, theta, lower-1-alpha, lower-2-alpha and upper-alpha) a three-factorial ANOVA with Scheffé tests on the 5% level for pairwise comparisons of means was performed. The factors and their levels are Method (FBFW, IBFW, IBIW), Time (t1, t2; i.e., two 500 ms intervals, one preceding, the other following the onset of a target) as a repeated measure, and Group (IAF+, IAF−) as a between-subjects factor. The levels for factor TIME are the two 500 ms epochs preceding and following the onset of the imperative stimulus. These intervals were selected because t1 (prestimulus) represents a time interval with high attention so that a strong desynchronization in the lower-1-alpha and the lower-2-alpha can be expected. On the other hand, t2 (poststimulus) represents an interval with a simple cognitive demand which is characterized by a synchronization in the theta and delta band (Klimesch et al. 1997b). Because these ANOVAs were performed to test the hypothesis whether subjects with high and low IAF respond in a similar way, the interaction Group × Method is of particular interest.

3 Results

3.1 Correlations

The correlation between IAF and TF shows a significant positive coefficient ($r = 0.467$, $P < 0.05$), indicating that a high IAF occurs together with a high TF. On the basis of this correlation, FBFW can be excluded. The highly significant and positive correlation ($r = 0.580$, $P < 0.01$) between IAF and the bandwidth (IAF−TF) rules out IBFW and supports IBIW. The respective regression lines are depicted in Fig. 3a and b.

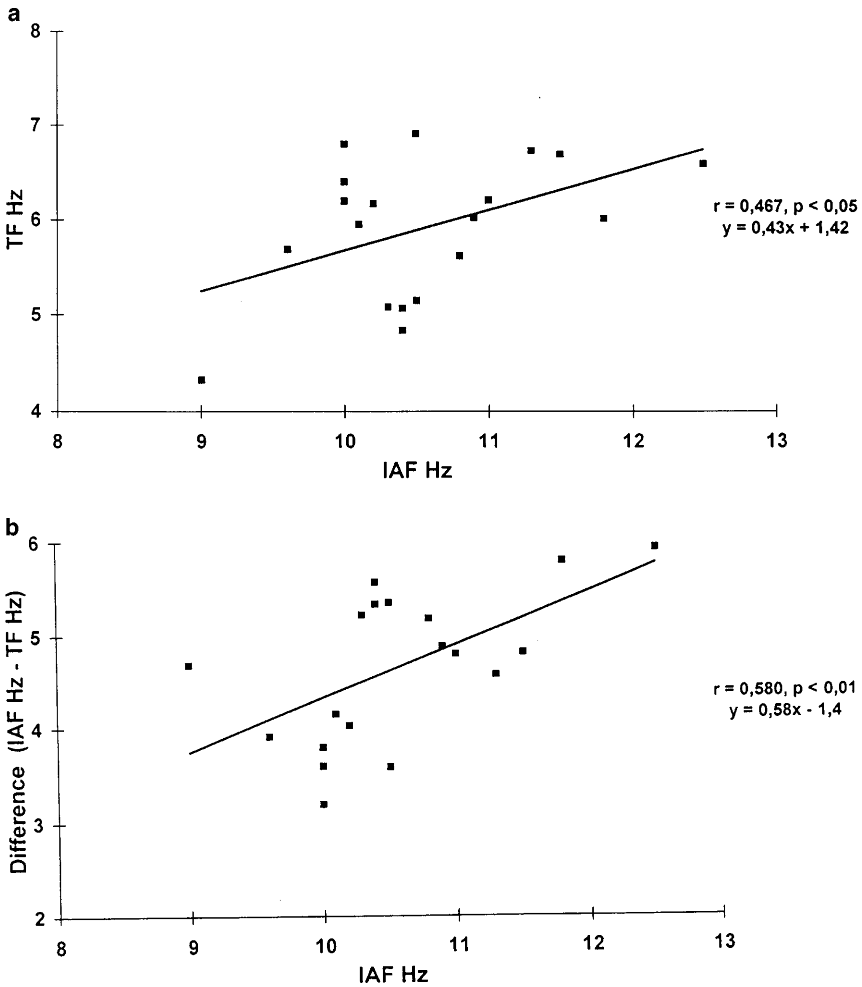

Fig. 3. a Regression lines and the respective correlations between TF and IAF and **b** between the difference (IAF − TF) and IAF **a** shows the significant positive correlation between TF and IAF. Most importantly, the highest correlation was obtained between the difference (IAF − TF) and IAF as **b** reveals. This supports the hypothesis that the frequency bandwidths also vary as a function of IAF, as explained in the Introduction

3.2 ANOVAs

For the delta band, only factor Time reached significance at the 1% level ($F = 60.08$, $P < 0.01$), showing a strong synchronization during t2.

For the theta band, significant effects were found for Method ($F = 13.86$, $P < 0.01$), Time ($F = 18.11$, $P < 0.01$), Group × Method ($F = 16.62$, $P < 0.01$), and Group × Method × Time ($F = 7.45$, $P < 0.01$). With respect to factor Method, the respective means indicate that synchronization is strongest for FBFW and weakest for IBFW. The means for factor Time reveal that, in contrast to t1, a pronounced synchronization was found during t2. For the means of interaction Group × Method, Scheffé tests for pairwise comparisons yield a critical difference of 10.65 ERD%. Inspection of Fig. 4a shows that significant differences at the 5% level between IAF+ and IAF− (marked with asterisks) were found for FBFW during t2 and for IBFW during t1 and t2 but not for IBIW.

The results for the lower-1-alpha bands show significant effects for Method ($F = 8.39$, $P < 0.01$) and for Group × Method ($F = 8.44$, $P < 0.01$). Here a moderate amount of desynchronization during t1 and t2 was found. The findings for factor Method reveal that the strongest desynchronization was obtained for IBFW and the smallest for FBFW. The Scheffé test for testing significance of differences on the 5% level between the means of interaction Group × Method reveals a critical value of 12.55 ERD%. As depicted in Fig. 4b, significant differences between IAF+ and IAF− can only be observed for FBFW during t2 and for IBFW during t1. Again no such effects can be observed for IBIW.

In the lower-2-alpha band, significant results were obtained for factor Time ($F = 15.09$, $P < 0.01$) and the interaction Method × Time ($F = 6.43$, $P < 0.01$). The respective means for TIME show a strong desynchronization that increases from t1 to t2. As Fig. 4c reveals, the significant interaction is largely due to the higher level of ERD for group IAF− during t2 which was found for FBFW.

In the upper-alpha band the only significant effect was found for Time ($F = 16.73$, $P < 0.01$), which shows an increase in desynchronization from t1 to t2.

4 Discussion

The results show that only for the proposed method (IBIW) were no significant differences obtained between the two groups of high and low alpha frequency (IAF+

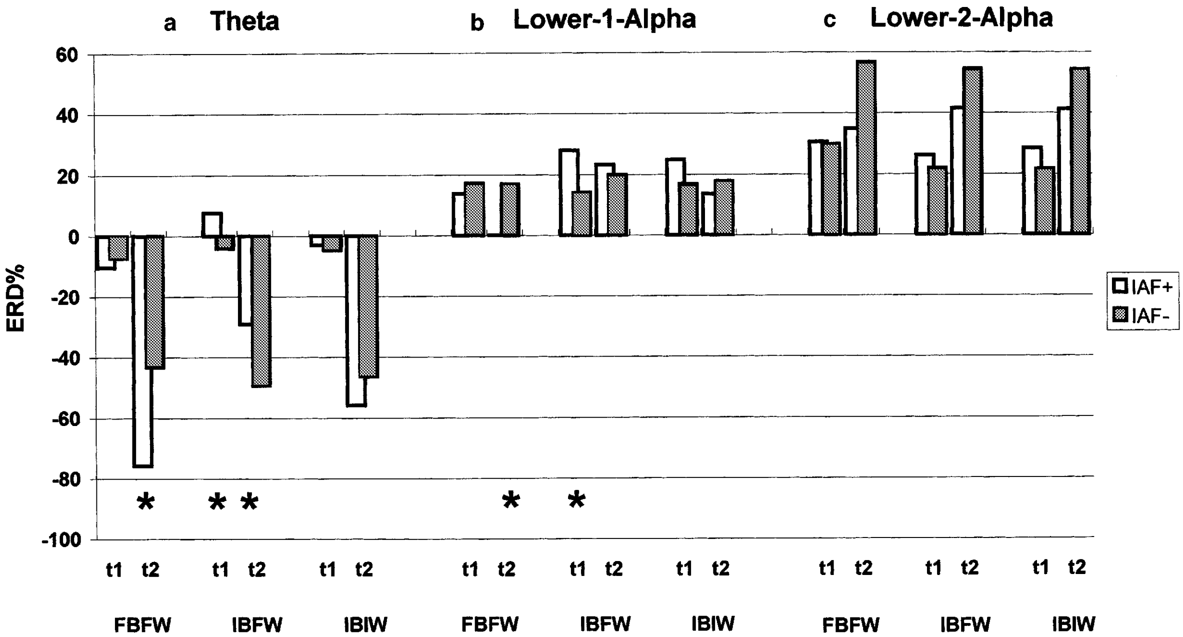

Fig. 4. The means of interaction Group × Time × Method are shown for the theta, lower-1-alpha, and lower-2-alpha bands. Factor Group comprises IAF+ and IAF− (n for IAF+ = 9, n for IAF− = 10), factor Time includes the two time intervals t1 and t2 (see Fig. 2), and Method comprises IBIW, IBFW, and FBFW. Significant differences as determined by Scheffé tests on the 5% level between group IAF+ and IAF− are marked with asterisks. In the theta and lower-1-alpha bands, significant differences between IAF+ and IAF− were observed only for FBFW and IBFW. Because no significant differences were found for IBIW, the assumption is supported that IBIW is superior to FBFW and IBFW

and IAF−). In sharp contrast to IBIW, large differences between these two groups were particularly obtained for the conventional method that uses FBFW, as Fig. 4 indicates. These findings demonstrate that interindividual differences in alpha frequency and bandwidth can be adequately treated when applying the proposed method.

The superiority of the proposed method can be documented by referring to the following two examples. First, let us consider the finding that the traditional method, FBFW, shows no desynchronization for IAF+ during t2 in the lower-1-alpha band (cf. Fig. 4b). In earlier experiments we have found consistently that, particularly in the lower alpha band, the presentation of a visual stimulus leads to a pronounced desynchronization with a very early onset that even precedes the presentation of a stimulus and most likely reflects expectancy (e.g., Klimesch et al. 1992). This lack of desynchronization which was found for FBFW can easily be explained by considering the fact that group IAF+ comprises subjects with comparatively high alpha frequency. Thus, the fixed lower-1-alpha band of group IAF+ already falls to a considerable extent below the lower boundary of the individual lower-1-alpha band. Consequently, either no or only a rudimentary lower alpha desynchronization can be detected. Another example well in line with this interpretation shows up in the theta band, where FBFW yields the largest amount of synchronization (cf. Fig. 4a). In a similar way as for the lower-1-alpha band, the fixed theta band of group IAF+ already falls in part outside the theta frequency range if individual bands with fixed widths are used. This finding is illustrated by Fig. 5, which shows that people with high IAF also have higher theta frequency and if fixed bands are not adjusted individually, theta synchronization already is confused with the much larger delta synchronization.

The transition frequency TF marks the upper frequency limit of the theta band. Thus, the positive correlation between IAF and TF clearly indicates that the theta band also varies interindividually and that about 22% of the variance of theta frequency can be explained by variations in alpha frequency. In addition, the correlation between IAF and the difference between TF and IAF demonstrates a close covariation between the bandwidth (i.e., the difference IAF−TF) and alpha frequency (IAF), which explains about 34% of the variance. Based on the results of the correlation anaysis and the predictions discussed in Sect. 2.7, IBIW (which is superior to FBFW and IBFW) can be accepted. Comparing the predicted relationship between IAF and TF with the actual data in Fig. 6 reveals that IBIW gives the best estimates. The regression line for the actual data is highly similar with the predicted regression line for the proposed method but quite different from the predicted regression lines for FBFW and IBFW.

Taken together, the reported results argue for the use of individually adjusted frequency bands when event-related band power measures of different types are used (Petsche and Rappelsberger 1992; Dujardin et al. 1995; Neubauer et al. 1995; Krause et al. 1996; Weiss and Rappelsberger 1996). It also appears likely that the individual determination of EEG frequencies may even prove useful for the analysis of ERPs (Basar et al. 1992; Basar-Eroglu et al. 1992; Basar and

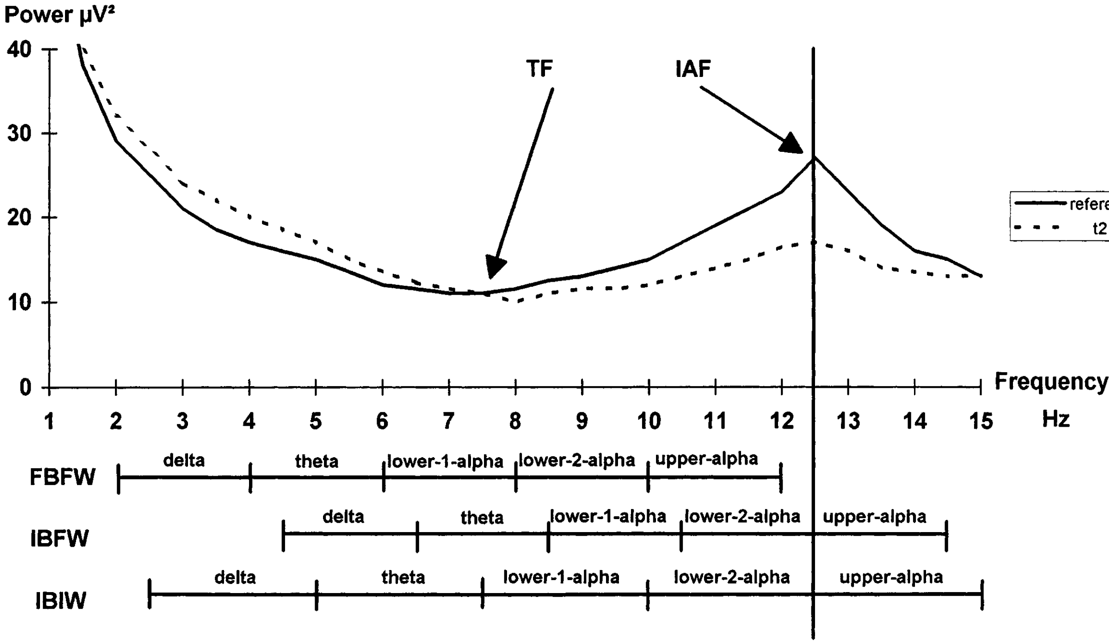

Fig. 5. Hypothetical power spectra for a subject with a comparably high IAF of 12.5 Hz. The three different methods (FBFW, IBFW, and IBIW as discussed in the text) yield different frequency bands, as shown in the lower part of the figure. Note that only IBIW covers the entire spectrum. The *bold line* (representing the reference interval) and the *dashed line* [representing period t2 (see Fig. 2)] intersect at TF, which marks a transition between theta synchronization and alpha desynchronization

Schürmann 1994). Basar and his research group have provided convincing evidence that event-related potentials (ERPs) under certain conditions are composed at least in part of phase-locked alpha activity (e.g., Basar and Schürmann 1994; Schürmann and Basar 1994). According to Basar (1972), phase-locked EEG activity as reflected by certain ERP components can be considered a resonance phenomenon that plays an important role in biological cybernetics. For future research in the increasingly important field of alpha oscillations (Basar et al. 1997) it will be interesting to determine whether alpha resonance phenomena show the same type of interindividual variability with respect to IAF and bandwidth as we have found in the present study for ERD. If this would indeed be the case, good arguments would be at hand to assume that spontaneous and resonant alpha activity are just different aspects of the same neural phenomenon.

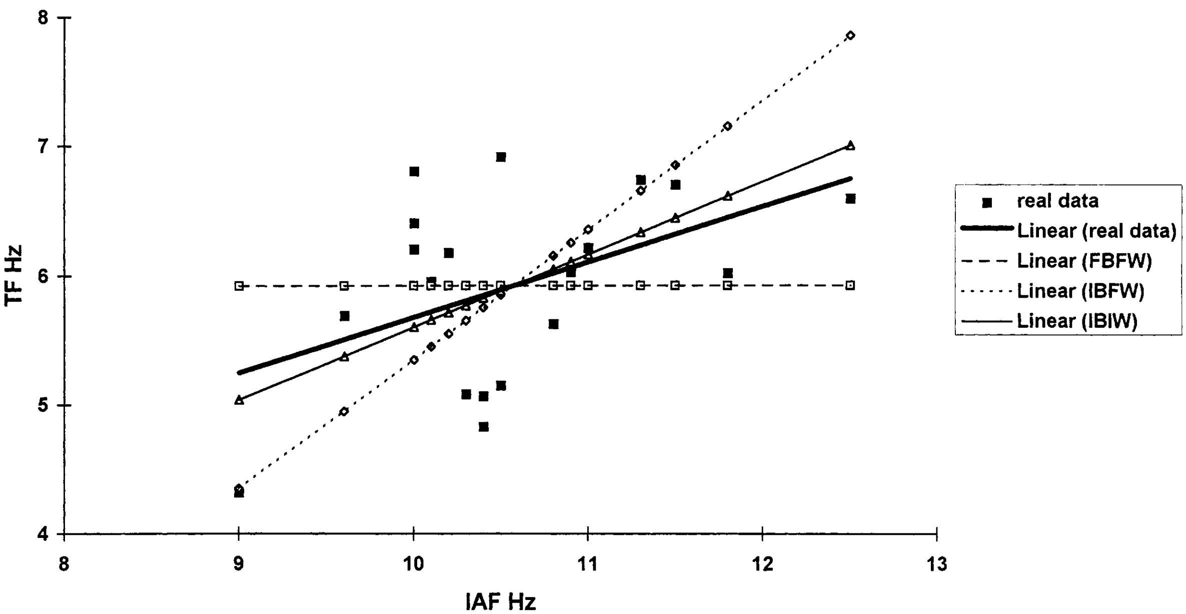

Fig. 6. The actual data and the respective regression line are added to the hypothetical lines for all three methods. In contrast to FBFW and IBFW, the regression line for IBIW gives the best estimates for the data obtained

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