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Theta band power changes in normal and dyslexic children

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Abstract

Objective: Tonic and phasic (event-related) theta band power changes were analyzed in a sample of 8 dyslexic and 8 control children. Previous research with healthy subjects suggests that electroencephalograph (EEG) theta activity reflects the encoding of new information into working memory. The aim of the present study was to investigate whether the processing deficits of dyslexics are related to a reduced phasic theta response during reading.

Method: The EEG was recorded while subjects were reading numbers, words and pseudowords and analyzed in a lower and upper theta band (4–8 Hz). A phasic response is measured in terms of an increase in event related band power during reading with respect to a reference interval. Tonic power is measured in terms of (log) band power during a reference interval.

Results: Large group differences in tonic and phasic lower theta were found for occipital sites where dyslexics show a complete lack of pseudoword processing. For words, only controls show a highly selective left hemispheric processing advantage.

Conclusions: Dyslexics have a lack to encode pseudowords in visual working memory with a concomitant lack of frontal processing selectivity. The upper theta band shows a different pattern of results which can be best interpreted to reflect the effort during the encoding process. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Dyslexia; Theta; Alpha; Attention; Memory; Event related desynchronization/synchronization; Event related theta band power

1. Introduction

The aim of the present study is to apply a new approach for the analysis of tonic and phasic (= event-related) band power changes to study brain dysfunctions in dyslexic children. This approach is based on rich empirical evidence (reviewed in Klimesch (1999)), which demonstrates that electroencephalograph (EEG) oscillations in the alpha and theta band reflect cognitive and memory performance in particular if a double dissociation between the type of EEG response (tonic versus phasic) in two different EEG frequency ranges (in the alpha and theta range) is taken into account. This double dissociation is given by two facts. First, it is well known that with increasing task demands, phasic band power increases in the theta but decreases (desynchronizes) in the alpha frequency range. Second, the extent of a phasic (event-related) EEG response depends at least in part on the extent of tonic power but in opposite ways for the theta and alpha frequency range. Whereas small tonic theta power enhances theta synchronization, large tonic alpha power enhances alpha desynchronization. Tonic power can be measured either during a reference interval, which typically precedes the presentation of an imperative stimulus (cf. Pfurtscheller and Aranibar, 1977) or during a resting condition at the beginning or end of the experimental session. In a pure theoretical sense, tonic power represents baseline power 'that should not be effected by any experimental effects'. Because this is almost never the case, the terms 'reference' and 'tonic' power may be used synonymously in a pragmatical sense. This definition also makes clear that phasic power – reflecting the short-lasting effects of stimuls presentation and/or task performance – must be measured in relation to tonic power.

In this paper we focus on the theta frequency range. A companion paper applies the same approach to the alpha and beta band. With respect to the theta frequency range, we have found good evidence that a phasic increase in a narrow frequency band of 2 Hz width (lying 4 Hz below the individually defined alpha frequency) reflects encoding processes of a working memory system (Klimesch et al., 1994, 1996, 1997a,b,c). As an example, we have found

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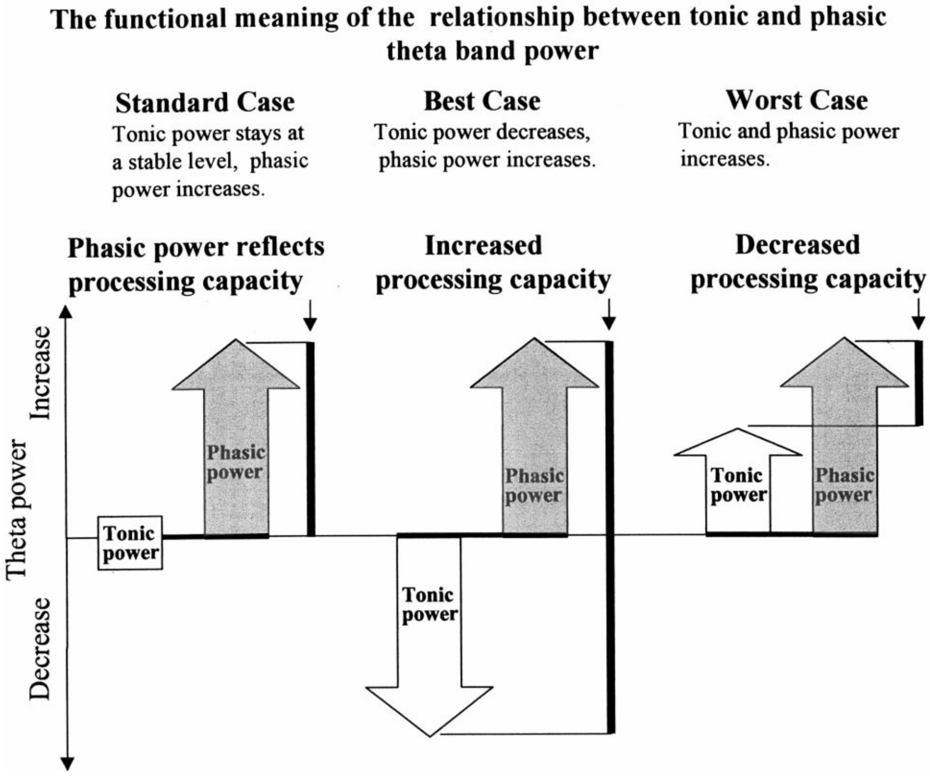

Fig. 1. The measurement and dissociation between tonic and phasic theta power.

that during encoding, words that can be remembered in a later free recall task exhibit a significantly larger phasic increase in theta power than words which cannot be remembered later (Klimesch et al., 1996). In a similar way, during successful retrieval in a word recognition task, correctly recognized words show a significantly larger phasic theta response than correctly identified distractors and false alarms. Other research groups have reported similar results (Gevins et al., 1997; Kahana et al., 1999; Tesche and Karhu, 2000). The interpretation of these and related findings is that the strength of a phasic theta power increase reflects to what extent processing resources of the working memory system are accessed.

It is important to note that the suggested interpretation is valid only, if tonic power stays at a stable level. As Fig. 1 illustrates, this is considered the ‘standard case’. Tonic power is typically measured during a reference interval that precedes the presentation of a stimulus whereas phasic power is typically measured during and/or after the presentation of a stimulus (see lower part of Fig. 2). The black bars in Fig. 1 indicate that the extent of a change in phasic band power should be evaluated together with changes in tonic band power. In a recent review (Klimesch, 1999) it was demonstrated that tonic power is increased under conditions that are associated with reduced cognitive processing capacity (e.g., in neurological diseases, slow wave sleep or fatigue), but is decreased under conditions that are associated with increased capacity (e.g., during high alertness). We have found experimental evidence that an increase in tonic theta reduces, but a decrease enhances a phasic response (Doppelmayr et al., 1998). Thus, we may distinguish a ‘best case’ from a ‘worst case’. The best case is characterized by a decrease, the ‘worst case’ by an increase in tonic power. If we assume that tonic power represents ‘background activity’or ‘system noise’ and phasic power the processing of the ‘signal’, the best case reflects a high and the worst case a low signal to noise ratio.

The logic as outlined in Fig. 1 will be applied for data analysis of the present experiment. We have recorded the EEG from a sample of dyslexic and control children in a reading task. In different blocks of trials, subjects were presented numbers, words and pseudowords. They were instructed to silently read each item and to pronounce it after a question mark appeared. The analysis of the EEG focused on the encoding period when subjects were reading. The basic idea is that – particularly for dyslexics – reading of pseudowords is the most difficult and reading of numbers the easiest task. Reading of pseudowords is commonly considered to be the most diagnostic symptom of dyslexia (e.g., Stanovich, 1994) and our research with German-speaking dyslexic children has confirms this position for a regular orthography (Wimmer, 1996).

Phasic theta is measured in terms of a change in event related theta band power (ERBP) during the poststimulus

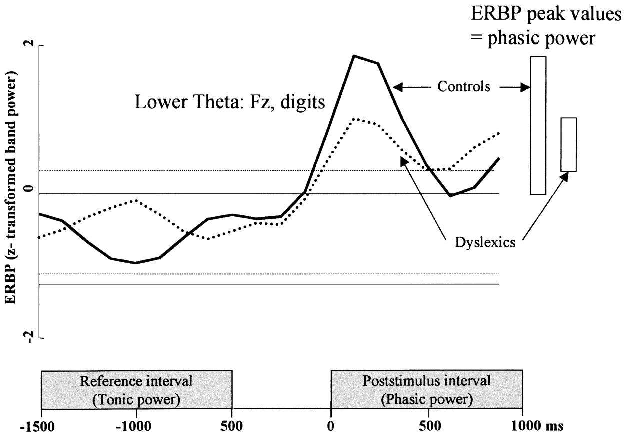

Fig. 2. An example showing a phasic band power change as measured by ERBP in the lower theta band (cf. Section 2). ERBP (or IBP) peak values are indicated by white and grey bars respectively. These values were used for plotting the results in Figs. 3 and 4. They are defined as the maximal phasic response (measured in z-units) exceeding the upper confidence interval (cf. Section 2).

period with respect to the reference interval (cf. Figs. 1 and 2 and the Section 2). Tonic power is measured in terms of theta band power during a reference interval preceding the presentation of an item. With respect to the terminology it should be noted that 'ERBP' is a neutral term that does not carry any a priori implications with respect to the existence of a particular type of oscillation in the scalp EEG. In contrast, the well known term event related desynchronization or synchronization (ERD/ERS) implies the existence of a spectral peak within that frequency range in which band power measures are calculated (Pfurtscheller and Lopes da Silva, 1999). Because only the broad alpha frequency band of about 7.5 to 12.5 Hz fulfills this requirement, it is recommendable to use a more neutral term, such as 'ERBP' if: (i) frequency bands outside alpha are analyzed; or if (ii) subbands within the broad alpha band are distinguished because in this latter case there usually are not separate alpha peaks, e.g. the lower and upper alpha.

The basic predictions are that: (i) the extent of a phasic theta response (in the standard case) is generally diminished for dyslexics; that (ii) the 'worst case' will be observed particularly when dyslexics try to read pseudowords; and that (iii) changes in tonic power reflect task difficulty. Data processing is done in 3 steps. First, we determine the extent of change in phasic theta power – as illustrated in Fig. 2 – for each recording site and each of the 3 tasks (processing of numbers, words and pseudowords). Second, tonic band power is compared between tasks to determine whether task related changes can be observed. Third, depending on the outcome, the results are categorized according to the 3 cases as illustrated in Fig. 1. The standard case is assumed if tonic power does not differ significantly between tasks. The best case is assumed if task related differences in tonic power are statistically significant and if tonic power decreases with increasing task difficulty. The worst case is assumed if task related differences in tonic power are statistically significant and if tonic power increases with increasing task difficulty. For the 'best case' we may assume that subjects have successfully increased their processing capacity in the most difficult condition. For the 'worst case' we assume that subjects are incapable to increase their processing capacity with increasing task difficulty.

Because it is well known that the event related increase in theta band power (as measured e.g., by ERBP) may be due at least in part by evoked theta activity (Basar, 1999), we also apply a measure which is termed 'induced band power' (IBP) and which is obtained by subtracting evoked theta on a single trial basis (Pfurtscheller and Lopes da Silva, 1999; Kalcher and Pfurtscheller, 1995; and Kaufman et al., 1989). By 'induced' theta we understand changes in theta band power that are modulated by stimuli or events and which – in contrast to evoked theta – do not respond in a phase locked manner (for a similar but much broader definition see Bullock (1992) Bullock, (1992)). There is evidence that induced EEG activity reflects more complex cognitive processes, whereas the evoked response reflects primarily stimulus driven processes (Tallon-Baudry and Bertrand, 1999). Thus, the analysis of induced theta band power will be useful, because we expect that this type of EEG activity will be particularly large for pseudowords and may distinguish well between dyslexics and controls.

Under conditions where phase locked activity is lacking, ERBP equals IBP. On the other hand, in cases where phase locked activity is large, IBP will be much smaller than ERBP. For this latter case it will also be of interest, to compare phase locked theta with the event-related potential (ERP). This will allow us to determine whether and to what extent phase locked theta influences certain ERP components.

To our best knowledge phasic band power changes have not yet been studied in dyslexic subjects. Thus, predictions for the present experiment can hardly be made on the basis of other EEG studies measuring more global power changes. In all of these studies the EEG (spectral or band) power was analyzed not trial per trial but instead either during a resting period (e.g., Harmony et al., 1995) or during the entire task period (e.g. Ackerman et al., 1998; Flynn et al., 1992; Galin et al., 1988; Ortiz et al., 1992; Rippon and Brunswick, 1998, 2000; Rumsey et al., 1989). If task related differences in power were calculated, this was done in terms of differences between a resting and task or between task conditions. Divergent results were obtained. As an example, Rippon and Brunswick (1998) found larger theta power and a more pronounced increase in task related theta power (Rippon and Brunswick, 1998, 2000) whereas other studies report no or only marginal changes in theta.

2. Method

2.1. Subjects

Two samples of 8 boys each (controls: mean age = 11.36

years; SD = 0.33; dyslexics: mean age = 11.6; SD = 0.5) participated in the experiment after informed consent was obtained. All subjects were right-handed. Handedness was controlled by asking the subjects about the hand they use in different tasks such as handwriting, throwing a ball, brushing teeth, etc. A subject was considered right-handed if he indicated to use the right hand for all of these different tasks.

Dyslexic subjects were selected from a longitudinal study according to the following criteria. (i) They were required to reach a non-verbal IQ (PTCS; c.f. Huttenlocher and Cohen-Levine, 1990) of at least 85; and (ii) a maximal percentile of a combined reading score of 8 as assessed by the Salzburg reading and Spelling Test (Landerl et al., 1997). This test consists of 5 subscales including reading abilities for words and non-words. For each subscale the dependent measure is the time needed to read a list of items, divided by the number of correctly read items. The maximum percentile of 8 indicates slow and/or inaccurate reading performance.

Controls were randomly selected from the same schools as the dyslexics. Selection criteria were: (i) same sex, age and right handedness (see previous); (ii) a comparable nonverbal IQ (mean and SD for controls: 108,7, 13.6; dyslexics: 98,4, 11.5); and (iii) average reading and spelling performance. As an example, in subtest 1 of the Salzburg reading and Spelling Test, controls read 88.4 words per minute (SD = 9.4), whereas dyslexics read only 30.8 words.

2.2. Material

A set of 75 two digit numbers (e.g., 13, 69), 75 corresponding number words (e.g., thirteen, etc.) and 75 pseudowords were used as stimuli.

2.3. Design and procedure

The experiment consisted of 3 parts, the number, word and pseudoword task. In each task 75 stimuli were presented. Subjects were instructed to pronounce each stimulus. They were told to wait until a question mark appeared on the screen. The interstimulus interval (i.e. the time between presentation onsets) was 5.5 s in the number and 6.5 s in the word and pseudoword task. The structure of a single trial consisted of a blank interval of 1.5 s (0–1500 ms), the presentation of a number for 1 s (1500–2500 ms) or the presentation of a word or pseudoword for 2 s (1500–3500) a blank interval of 5 s, the presentation of a question mark for 1 s and a blank interval of 1.5 s.

Subjects sat at a distance of 1.4 m from the monitor. The numbers or words appeared at the centre of the monitor and were 3 cm in height. The length of a word with 10 letters was 23 cm.

The interesting research of Bastiaansen et al. (1999) and Brunia (e.g., Brunia, 1993) have shown that as a consequence of periodic stimulation, a negative shift and desynchronization can be observed prestimulus. Consequently, anticipation may influence reference power. On the other hand, we have shown that ‘aperiodic’ stimulation (by using intertrial intervals varying randomly in their duration) leads to changes in attention, which also have a strong influence on bandpower in the prestimulus interval (Klimesch et al., 1992). In order to avoid strong biasing effects which are due to anticipation, we used a reference interval (of 1 s) that ends already 500 ms before a stimulus is presented.

2.4. Apparatus

EEG-signals were amplified by a 32-channel 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 via a 32-channel A/D converter. Sampling rate was 128 Hz. During data acquisition, EEG signals were displayed online on a high resolution monitor and stored on disk.

2.5. Acquisition and processing of EEG-data

A set of 15 silver electrodes – attached with a glue paste (Nihon Kohden Elefix EEG paste) to the scalp – was used to record EEG-signals. Electrode diameter was 1 cm. The electrodes were placed according to the International Electrode (10-20) Placement-system, at F3, F4, Fz, FC5, FC6, C3, C4, Cz, CP5, CP6, P3, P4, Pz, O1 and O2. All data were recorded referentially against a common reference placed on the nose. In addition to these 15 electrodes, two earlobe electrodes (termed A1 and A2), were attached to the left and right ear. Furthermore, the electrooculogram (EOG) was recorded from two pairs of leads in order to register horizontal and vertical eye movements.

Data were recorded against a common reference placed on the nose and off-line algebraically re-referenced to linked earlobes.

All of the epochs in each task were carefully checked individually for artifacts (eye blinks, horizontal and vertical eye movements, muscle artifacts, etc.) by visual inspection. Because low EEG frequencies may very easily get contaminated by eye movements, a very strict criterion for rejecting eye movement artifacts was applied: Epochs that were associated even with small changes in the horizontal or vertical EOG-channel within an interval of 1 s preceding and following the presentation of a stimulus were rejected. This screening was done by visual inspection. After rejecting artifacts and erroneous trials, an average of 48, 32 and 28 epochs remained for the number, word and pseudoword task, respectively.

2.6. The calculation of event-related band power (ERBP)

Because we have shown repeatedly that the use of fixed frequency bands leads to distorted results (cf. the summary in Klimesch (1999)), we use adjusted bands. This was done for each group i of subjects by using alpha frequency AF(i) as a cut-off point between the lower and upper alpha band which are defined as bands with a width of 2 Hz falling below and above AF(i). Alpha frequency is defined as mean frequency, calculated over the entire epochs of all 3 tasks and averaged for all leads and subjects in each group. For the present study, we distinguish a lower and an upper theta band (with a width of 2 Hz), which lie below the frequency limits of the alpha band: Lower theta: AF(i) – 4 Hz to AF(i) – 6; Upper theta: AF(i) – 2 Hz to AF(i) – 4Hz. Mean alpha frequency was 9.75 Hz.

As described in Klimesch et al. (1998b), the different steps for calculating ERBP are the following. First, over the entire length of the experimental session, the EEG data are band pass filtered and then the filtered data are squared. Segmentation into single trials is done after band-pass filtering. Second, the obtained data are averaged over the number of artifact free epochs. Third, within consecutive time windows of 125 ms the squared data are averaged. Fourth, z-values were computed for each subject, recording site and experimental condition to obtain data that are Gaussian distributed.

2.7. The calculation of induced band power (IBP)

The calculation of ERBP and IBP is identical with the following exception referring to step 1. For each sample point i of the band pass filtered data $x(i,j)$, the mean $\mu(i)$ – representing the ERP of the band pass filtered data – is calculated over the $j = 1 \ldots n$ epochs for each electrode site, experimental condition and subject (cf. Klimesch et al., 1998b). Then, the differences between the filtered data $x(i,j)$ and the mean $\mu(i)$ is squared: $x'(i,j) = [x(i,j) - \mu(\mathrm{i})]^2$. Then, as for ERBP, the obtained data are averaged and z-values were computed. These z-transformed power values are termed IBP or (in the case the band pass filtered ERP is not subtracted) ERBP.

A small IBP value reflects a large influence of evoked activity. It should be noted that the influence of the band pass filtered ERP can be estimated by looking at the difference between ERBP and IBP (cf. Figs. 3 and 4). If both measures are of equal magnitude, there is no influence of evoked activity.

Although squared power values are chi square distributed, the calculation of z-values is justified because of the following reasons. The form of the chi square distribution depends on sample size n, and beyond $n = 30$, the chi square distribution takes the form of a normal distribution. The calculation of z-values is based on averaged power values with sample sizes exceeding $n = 30$. In our case, n represents the number of trials or epochs.

2.8. The calculation of tonic power

The calculation of tonic band power is identical with that for ERBP with the exception of calculation step 4 (the computation of z-values). Tonic band power was calculated only for the first second of each trial, which is considered the reference interval or 'baseline' for each trail.

2.9. The calculation of phasic power

As illustrated in Fig. 2, phasic power was calculated in terms of ERBP or IBP peak values (in the poststimulus interval of 0–1000 ms), which are defined as maximal band power changes in relation to the confidence limits of the reference interval (cf. lower part of Fig. 2). The confidence intervals were calculated by using the means and variances of the respective data (for each lead and experimental condition) of each sample of subjects. The significance level was set at 0.1%.

Thus, ERBP and IBP peak values (cf. the vertical bars in Fig. 2) represent the maximal change in band power post-stimulus (in z-units) in relation to the mean and variance of the reference interval, which we consider error variance. We argue that this simple procedure gives a good visualization of the significance of a phasic change: The evaluation of the extent of a phasic change depends (besides other factors) on a stable reference interval. If it is stable in statistical terms, the variance (reflected by the width of the confidence interval) is small and consequently, only a small value is subtracted in addition to the mean of the reference interval. On the other hand, if the error variance is large, the extent of a phasic change is proportionally reduced.

2.10. Statistical analyses

ANOVAs were calculated to evaluate differences in tonic band power. The factors and their levels are GROUP (dyslexics vs. controls), TASK (numbers, words, pseudowords) and LOCATION. For frontal (F3, Fz, F4), fronto-central (FC5, FC6), central (C3, Cz, C4), centroparietal (CP5, CP6), parietal (P3, Pz, P4) and occipital (O1, O2) recording sites and each of the 5 frequency bands separate ANOVA's were calculated. The Greenhouse–Geisser procedure was used to compensate for violations of sphericity or circularity. For repeated measurement factors with more than two levels, the adjusted tail probabilities are reported below. Because we are primarily interested in task-related influences on tonic power, significant findings are reported only for factor TASK and any interaction in which this factor is involved.

3. Results

3.1. Behavioral data

The number of incorrect pronounciations for controls and dyslexics were one and 3 in the number task, 5 and 5 in the word and 19 and 161 in the pseudoword task.

3.2. Phasic lower theta

An example of the time course of band power changes in the theta band is shown for Fz in Fig. 2. Theta ERBP peak

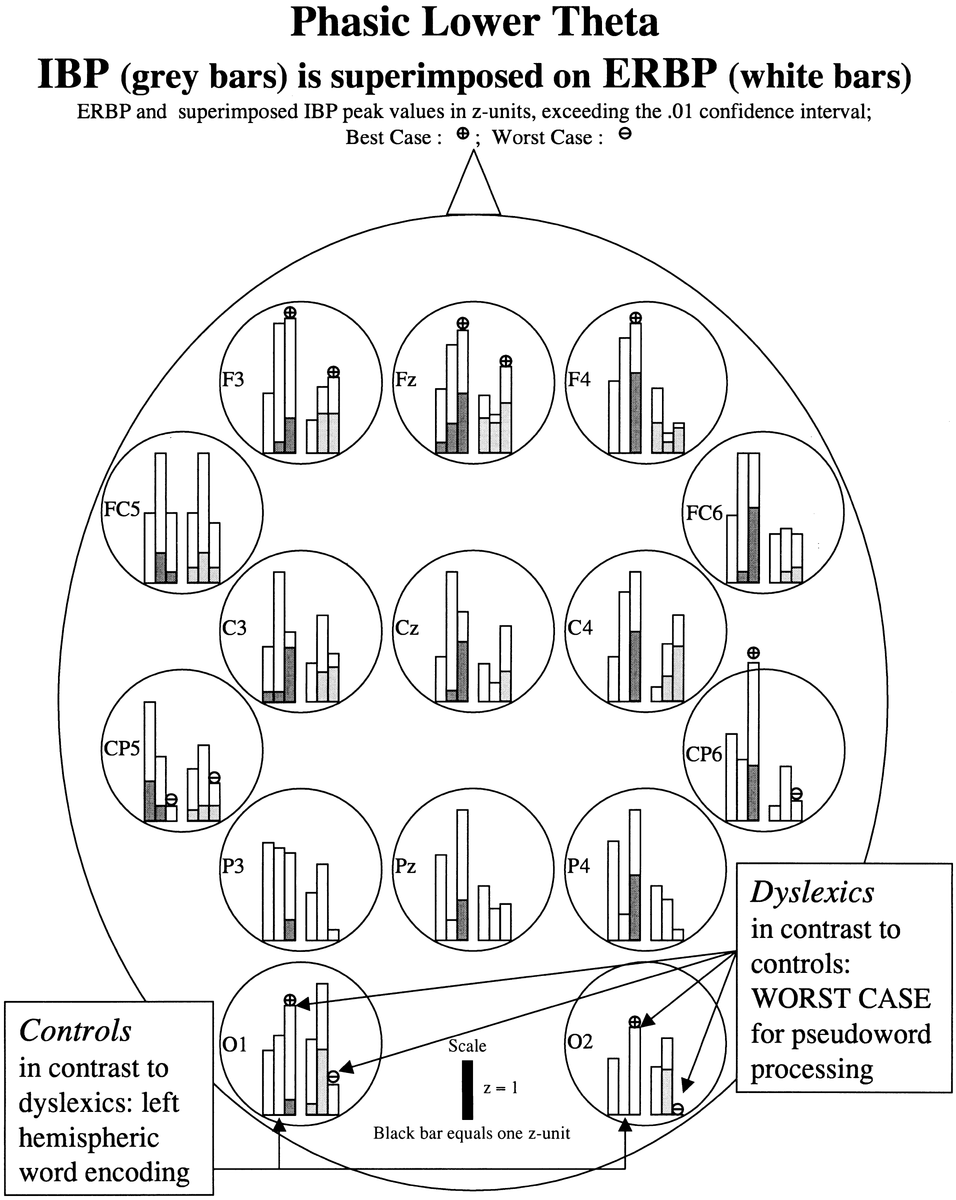

Fig. 3. The results for the lower theta band. At each recording site, 6 bars are plotted. The first 3 represent the findings for the control group, the last 3 those for dyslexics. From left to right (for each group and recording site), the first, second and third bar represent the data for the number, word and pseudoword task, respectively. IBP peak values (shown in grey) are superimposed on ERBP peak values (represented here by white bars). The influence of evoked activity is reflected by the difference between white and grey.

values are depicted in Fig. 3 as white bars. With the exception of O2 a significant, event-related increase in band power was found for both groups in all of the 3 tasks and recording sites. At O2, however, dyslexics fail to show a significant increase in theta during the processing of pseudowords, whereas controls fail to show a significant increase for words.

3.3. Tonic lower theta

A main effect for TASK was found only for frontal sites ($F(2,28) = 3.35$; $P < 0.05$) but significant interactions involving TASK were also found at centroparietal (TASK × LOCATION × GROUP, $F(2,28) = 3.65$; $P < 0.05$) and occipital sites (TASK × GROUP, $F(2,28) = 5.39$; $P < 0.02$). As the respective means indicate, tonic power decreases with task difficulty at frontal sites for both groups. At occipital sites and CP6 tonic power decreases with task difficulty for controls but increases at all sites for dyslexics.

The coincidence of an increase in phasic theta and a decrease in tonic theta with increasing task difficulty represents the best case which is found at frontal sites for both groups and at occipital sites only for controls. Best cases are marked by ‘ + ’ in Fig. 3. The worst cases are marked by ‘ − ’ and are found at CP5 for both groups and at CP6 and occipital sites only for dyslexics.

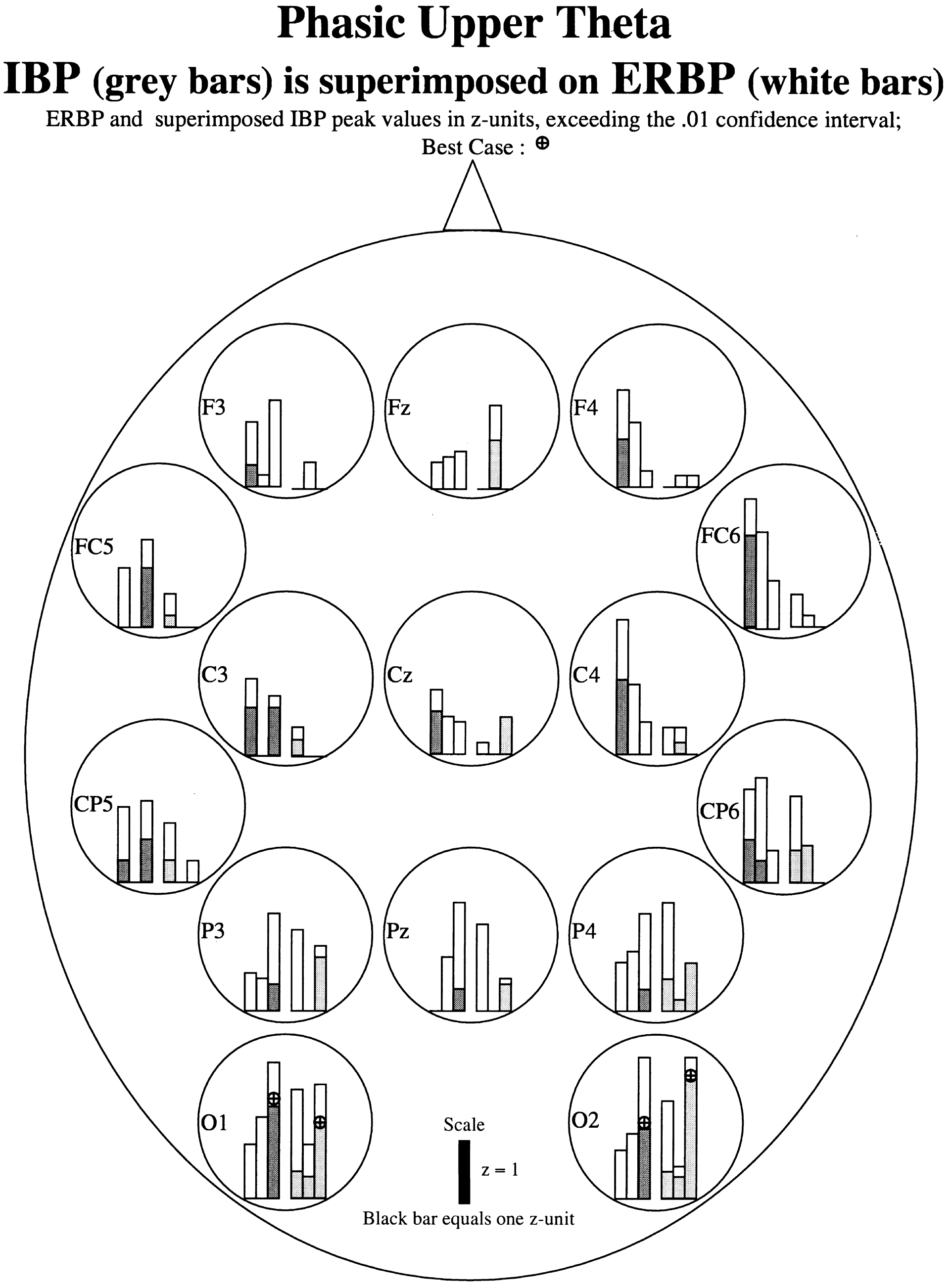

Fig. 4. The results for the upper theta band. At each recording site, 6 bars are plotted. The first 3 represent the findings for the control group, the last 3 those for dyslexics. From left to right (for each group and recording site), the first, second and third bar represent the data for the number, word and pseudoword task, respectively. IBP peak values (shown in grey) are superimposed on ERBP peak values (represented by white bars). The influence of evoked activity is reflected

3.4. Induced and evoked lower theta

The findings for induced band power in the lower theta band are summarized in Fig. 3 (superimposed on the ERBP values as grey bars). The influence of evoked power is particularly large in cases where the difference between white and grey bars is large. Inspection of Fig. 3 demonstrates that the influence of evoked theta is generally large because the number of significant findings for induced band power is reduced by about 50%. Large differences can be observed between tasks and groups. For the control group only 3 significant IBP findings remain for numbers (−80%), 7 for words (−50%) and 13 for pseudowords (−14%). For dyslexic subjects, 5 remain for numbers (−67%), 10 for words (−33%) and 9 for pseudowords (−36%).

Because ERBP and IBP are *z*-transformed power measures, the influence of the evoked response on absolute power as for example reflected in ERP amplitudes cannot be estimated by inspection of Fig. 3. In order to demonstrate the influence of evoked theta in terms of absolute power, the band pass filtered ERP's (also termed $\mu(i)$ in the Section 2) of the lower and upper theta are plotted together with the standard ERP's for Fz as an example in Fig. 5. A comparison of the filtered with the standard ERP's reveal that the peaks of the N1 and P2 as the main components of the ERP coincide nicely with the peaks of the theta ERP's. In addition, it should be noted that the peak to peak amplitudes (of N1 and P2) are larger for controls than dyslexics as is the case with the respective peaks of the theta ERP's.

3.5. Phasic upper theta

Compared with the lower theta band, the number of significant band power changes is somewhat smaller, as Fig. 4 demonstrates. For controls we find 41 significant changes but only 29 for dyslexics. This reduction is signif-

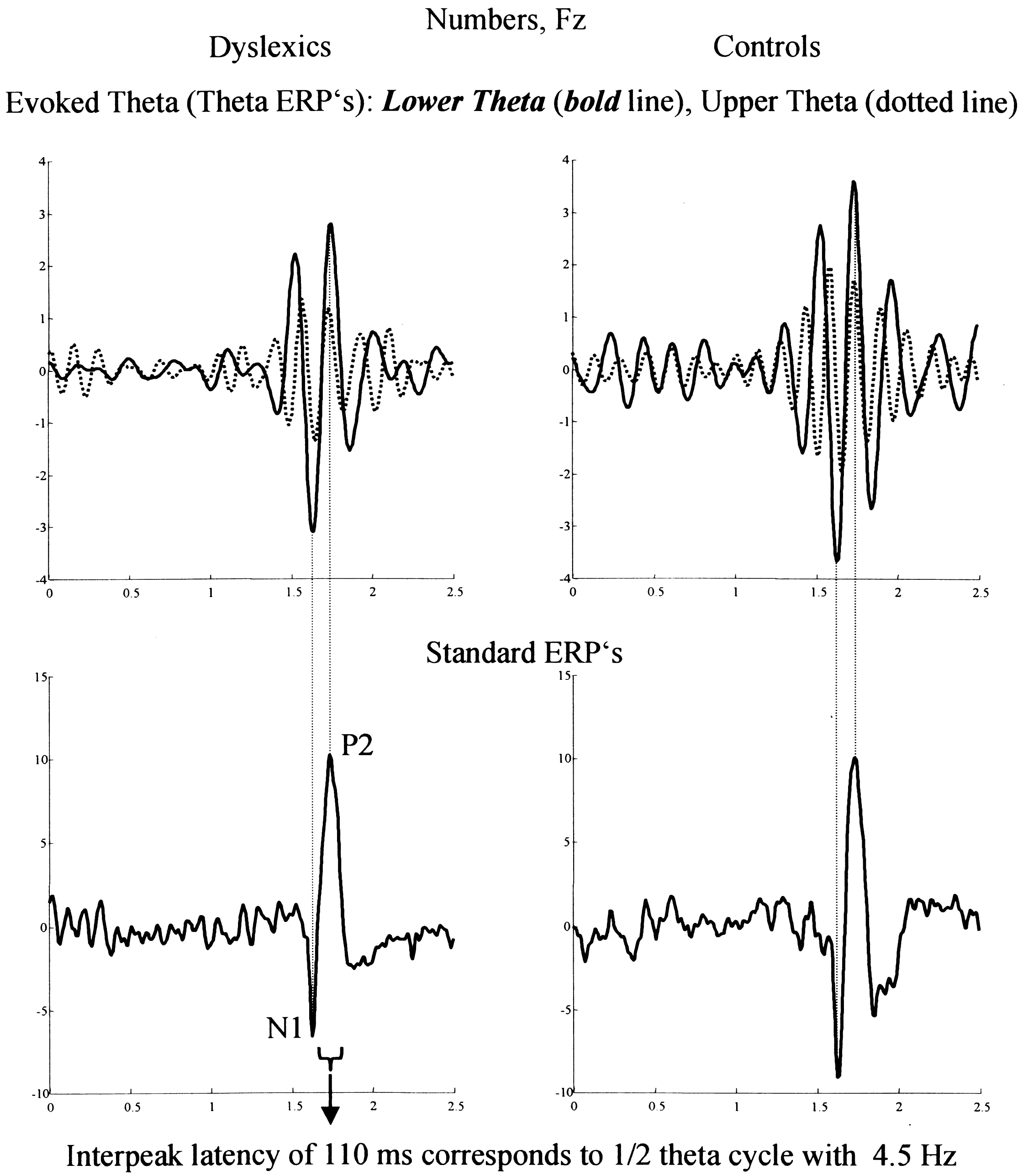

Fig. 5. The correspondence between evoked theta – as reflected by the ERP's of the band pass filtered data – and the main components of the standard ERP at Fz. Note the perfect correspondence between theta and ERP peaks as indicated by the vertical dashed lines. Note also that controls show larger evoked theta ERP's and a larger N1 to P2 peak to peak amplitude than dyslexics.

icant for dyslexics but not for controls (χ^2-test; expected frequency = 44; $\chi^2(\text{d.f.} = 1) = 5.32$, $P < 0.05$).

3.6. Tonic upper theta

The only significant finding is a main effect for TASK ($F(2,28) = 3.81$, $P < 0.04$) at occipital sites. The respective means indicate that pseudowords show the smallest power as compared to numbers and words.

Because at occipital sites pseudowords show the largest phasic response and the smallest tonic power, we observe 'a best' case at these sites for both groups (cf. Fig. 4). This is in sharp contrast to the respective findings in the lower theta band as a comparison with Fig. 3 demonstrates.

3.7. Induced and evoked upper theta

The respective findings are summarized in Fig. 4 (grey bars) and show again that compared to ERBP the number of significant IBP findings is much smaller. For the control group 8 significant IBP findings remain for numbers (−43%), one for words (−92%) and 8 for pseudowords (−47%). For dyslexic subjects, 7 remain for numbers (−42%), 6 for words (−33%) and 6 for pseudowords (−25%). It should be noted that for controls the increase in phasic upper theta for words is almost exclusively due to evoked upper theta activity.

Fig. 4 demonstrates that, the influence of evoked upper theta (difference between white and grey bars) appears larger at posterior as compared to central or anterior sites. In order to show the impact of evoked activity on the ERP, the theta and standard ERP's are plotted together in Fig. 6 for the number task at O1. At posterior sites the main ERP components (termed P1 and P2) are two positive peaks at about 100 and 200 ms poststimulus. These peaks coincide nicely with the theta ERP's. Most interestingly, as compared to Fz where mean theta frequency is 4.5 Hz (cf. Fig. 5), mean theta frequency is about 1 Hz higher at O1 (cf. Fig. 6).

4. Discussion

The findings show a frequency specific pattern of task and group differences. As mentioned in Section 1 the dissociation of tonic and event-related band power is considered an excellent indicator to what extent processing resources can be accessed. We first discuss this indicator, which can be best observed in the lower theta band at frontal and occipital sites.

In the lower theta band and at frontal sites, the 'best case condition' can be observed for both groups. Here, the event-related increase in theta power is larger for pseudowords than for non-words and is mirrored by a task related decrease in tonic power which is largest for pseudowords and smallest for numbers. This indicates that at frontal sites processing capacity can easily be increased if task demands become more difficult. At occipital sites, however, there is a reliable and interesting group difference. Whereas dyslexics show the 'worst case' for pseudoword processing at both sites, controls still show the 'best case'. This finding clearly demonstrates that unlike controls, dyslexics are unable to encode pseudowords. Because we assume that the lower theta band reflects processes of the working memory system, 'encoding' is here understood in terms of encoding into the working memory system. Another important and reliable group difference can be observed with respect to word processing at occipital sites. In contrast to dyslexics, controls show a highly selective left hemispheric processing of words as is indicated by the lack of a significant phasic theta increase at O2 and attenuated responses at Pz, P4 and CP6 (cf. Fig. 3). This finding indicates that in contrast to controls, dyslexics encode words bilaterally. Finally we have to consider the 'worst cases' at centroparietal sites. At CP5, a site which roughly corresponds to the angular gyrus, the worst cases indicate that both groups have no capacity to process pseudowords. At the right hemispheric site CP6, however, controls show an extremely large phasic response (exceeding two z-units) and a 'best case' for pseudowords, whereas dyslexics still exhibit the 'worst case'. This finding suggests that the angular gyrus (CP5) has no capacity to encode pseudowords and that control subjects encode pseudowords at the homologic right hemispheric site CP6 where (as compared to all other sites and task conditions) the largest phasic response was found.

The results for induced theta activity (in the lower band) complements the described findings and show in addition that only for controls induced activity is generally larger for pseudowords at most recording sites. Dyslexics, however, show clear topographical differences. As inspection of Fig. 3 reveals, dyslexics show an induced response for words at O1 and O2. Because there is good evidence that induced activity reflects the complexity of cognitive processes, this result indicates that word processing at occipital sites is a very complex task for dyslexics but not for controls. A similar interpretation applies for the processing of pseudowords in controls. At O1, parietal sites, CP6, C4 and F4 significant findings for induced activity are found only for pseudowords. Thus, we may conclude that controls process pseudowords at regions corresponding to these sites.

The upper theta band (cf. Fig. 4) shows a completely different pattern of results. Most striking is the fact that 'best cases' can be observed for both groups and at both occipital sites. At the first glance this result seems to contradict the respective findings of the lower theta band. However, if we assume that particularly the induced component of the upper theta response reflects the effort that corresponds to task difficulty, a consistent interpretation is made possible at least for findings obtained at posterior recording sites. For controls, a significant induced theta response can be observed at these sites only for pseudowords (cf. Fig. 4) whereas dyslexics show also an increase (but to a smaller extent) in response to words and numbers. Thus, this result

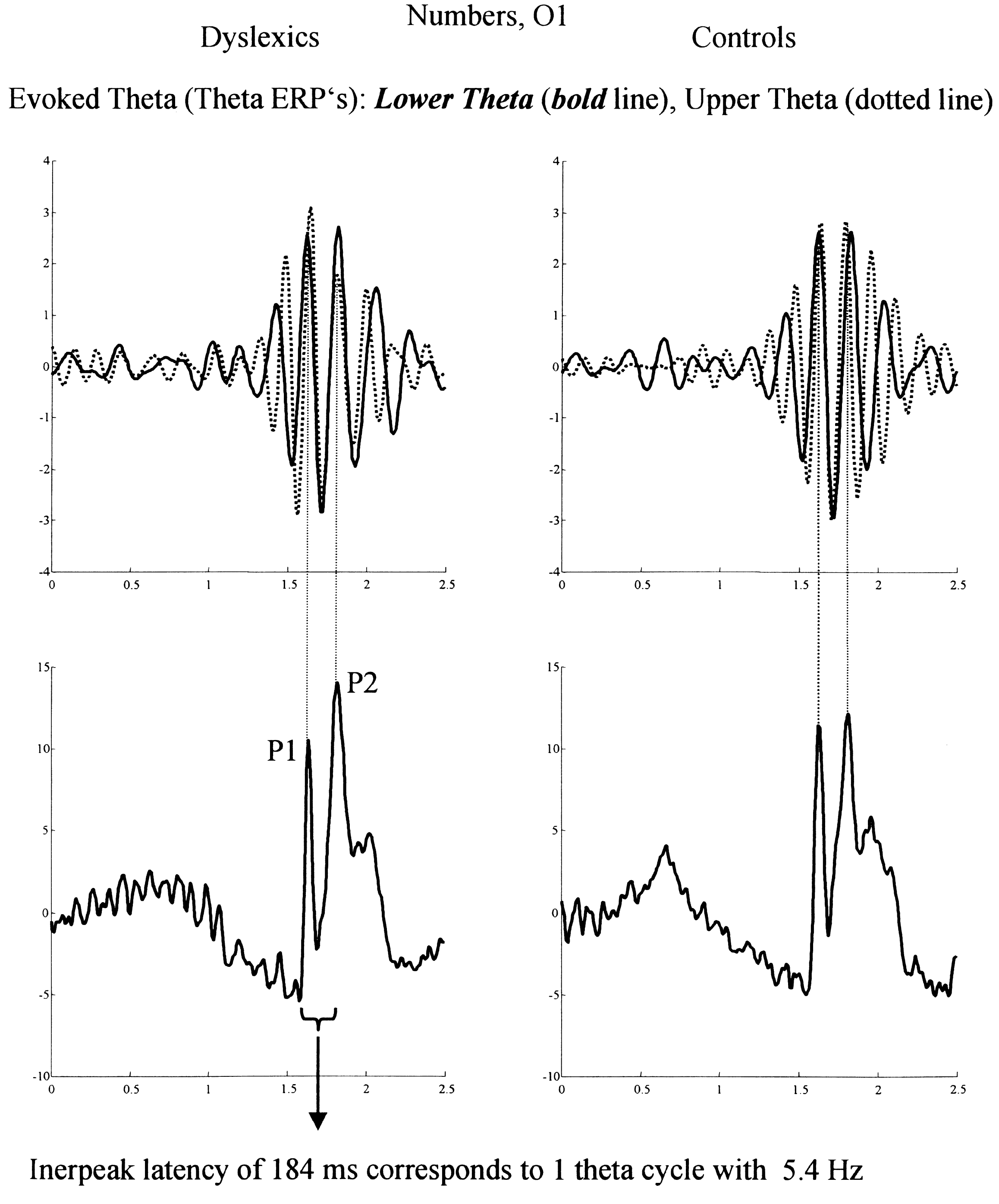

Fig. 6. The correspondence between evoked theta – as reflected by the ERP's of the band pass filtered data – and the main components of the standard ERP at O1. Note the perfect correspondence between theta and ERP peaks as indicated by the vertical dashed lines. A comparison with Fig. 5 reveals that (within exactly the same latency window) the N1 at Fz corresponds with a negative theta peak, whereas P1 at O2 corresponds with a positive theta peak. These findings suggest a phase reversal in theta activity between anterior and posterior sites.

may very well reflect the increased effort that is associated particularly with the processing of pseudowords. For anterior sites, the findings show a very heterogenous pattern which is difficult to interpret. It may be speculated that this difficulty is due to the fact that subjects were only instructed to read the presented items but not to perform any particular task (such as finding analogies to words or summing up numbers). Most likely, at least some subjects and particularly those of the control group were tempted to perform some operations with the presented items. The effort associated with the performance of these 'uncontrolled processes' may be reflected by these heterogenous findings at anterior sites. The fact that the number of significant findings is larger for controls than for dyslexics (cf. Fig. 4) particularly at anterior sites appears consistent with this interpretation. Controls most likely had more capacity and, thus, more opportunity to perform some additional operations.

It is important to note that the frequency characteristics of the standard ERP's (as shown in Figs. 5 and 6) is dominated by theta activity of about 5 Hz. This corresponds to exactly that frequency where (in earlier research, cf. Section 1) we have found a strong and consistent relationship between theta synchronization and encoding processes of the working memory system. It should also be noted that the results for the two frequency bands of the lower and upper theta (with just a width of 2 Hz) show striking differences (compare e.g., Fig. 3 with Fig. 4). These findings demonstrate that the use of broad frequency bands (a broad theta band of about 4–8 Hz) would mask potentially interesting results. The influence of theta activity on the standard ERP may be estimated by the interpeak latency of the main components (N1, P1 at frontal sites and P1 and P2 at posterior sites) which lies exactly in this frequency range. Furthermore, a large percentage of the magnitude of the N1, P1 and P2 amplitudes can be explained by evoked theta. As an example, the N1 amplitude for controls at Fz equals about 9 μV whereas the sum of the lower and upper theta amplitudes (peaking at exactly the same latency as the N1) equals about 5.5 μV. Thus, about 60% of the amplitude of the N1 can be explained by theta activity. Of course, these findings do not prove that ERP's are strongly influenced by evoked theta oscillations (as has long been suggested by Basar, cf. the review in Basar (1999)). Nevertheless, they provide strong support for the view that ERP components can be (at least in part) explained by evoked oscillations.

Finally, it should be emphasized that in all of our previous studies (which are all based on data from adult subjects) we used individually calculated frequency bands. In children, EEG frequencies may have a different meaning as compared to the adult EEG (for a review see Klimesch (1999)). Indeed, in the present study we found that the frequency range for an event-related increase in power (which is typical for theta) is twice as wide as in previous studies with adult subjects and covers a range of about 4–8 Hz. The frequency range of about 6–8 Hz which we, thus, termed 'upper theta' in the present study, corresponds to a frequency range that desynchronizes and was termed 'lower-1 alpha' in studies with adults (e.g., Klimesch et al., 1998a,b). Whether this finding reflects a certain developmental stage in brain maturation remains an open question, which would be promising to address in future research. The lack of knowledge about the functional meaning of EEG frequencies in children and rather small differences in individual alpha frequency (IAF), prevented us from using this measure to calculate individually adjusted frequency bands. The fact that all of the frequency bands show either an event-related increase or decrease in power (see the companion paper about alpha and beta) in both groups, all recording sites and all conditions suggests that the definition of frequency bands in the present study may be considered adequate. Nonetheless, further research will be needed for a better understanding of the functional meaning of EEG frequencies in different developmental stages.

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