Clinical Neurophysiology 112 (2001) 1186–1195

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Alpha and beta band power changes in normal and dyslexic children ☆

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Accepted 23 March 2001

Abstract

Objective: Previous research with healthy subjects suggests that the lower alpha band reflects attentional whereas the upper alpha band semantic processes. The aim of the present study was to investigate whether dyslexics show deficits in attentional control and/or semantic encoding.

Method: The EEG was recorded while subjects were reading numbers, words and pseudowords and analyzed in a lower and upper alpha and two beta bands (spanning a range of about 8–16 Hz). A phasic response is measured in terms of a decrease 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: In the lower alpha band dyslexics show an increased phasic response to words and pseudowords at right hemispheric sites but a lack to respond to words at O1. The upper alpha band exhibits a highly selective phasic response to words at left frontal sites but for controls only, whereas dyslexics show a general increase in tonic upper alpha power. Whereas the low frequency beta band (beta-1a) exhibits a rather diffuse pattern, a highly selective finding was obtained for the beta-1b band.

Conclusions: Dyslexics have a lack of attentional control during the encoding of words at left occipital sites and a lack of a selective topographic activation pattern during the semantic encoding of words. Because only in controls reading of words is associated with a strong beta-1b desynchronization at those recording sites which correspond to Broca's area (FC5) and the angular gyrus (CP5, P3), we may conclude that this frequency band reflects the graphemicphonetic encoding of words.

Keywords: Dyslexia; Alpha; Beta attention; Memory; Event related desynchronization/synchronization; Event-related band power

1. Introduction

The aim of the present study is to apply the same approach as described in our companion paper about theta to the alpha and slow beta frequency range. We assume that EEG oscillations in the alpha band reflect attentional and semantic memory processes if a dissociation between tonic and phasic band power changes is taken into account (see Klimesch, 1999; Klimesch et al., 2000a,b; for recent data). The extent of a phasic (event-related) EEG response (cf. Fig. 1) depends at least in part on the extent of tonic power (as measured in a 'baseline' condition, e.g. during a reference interval (cf. Pfurtscheller and Aranibar, 1977) or rest. We have found that large tonic alpha power enhances desynchronization, whereas small tonic power attenuates desynchronization (Doppelmayr et al., 1998).

Experiments from our laboratory suggest that desynchronization in the upper alpha band – a frequency band of 2 Hz width lying above the individually determined alpha frequency (IAF) – reflects semantic memory processes, whereas desynchronization in the lower alpha band – a frequency band of 2 Hz width lying up to 4 Hz below IAF – reflects attentional processes. The functional meaning of the upper alpha band was investigated in a study by Klimesch et al. (1994). Subjects first performed a semantic task in which they had to judge whether sequentially presented concept-feature pairs (such as 'eagle-claws' or 'pea-huge') are congruent. Then, without prior warning, they were asked to perform an episodic recognition task. Now, subjects had to indicate whether a particular concept-feature pair was already presented during the semantic task. Because pairs of items were presented, the episodic and semantic task can be performed only after the second item of a pair (i.e. the feature) is presented. Thus, the critical issue was to compare the extent of band power changes (in the theta, lower and upper alpha frequency range) during the presentation of the concept and feature word in the episodic and semantic task. The results show that during semantic processing, a significant decrease in

☆ This research was supported by the Austrian 'Fonds zur Forderung der wissenschaftlichen Forschung', Project P-13047.

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PII: S1388-2457(01)00543-0

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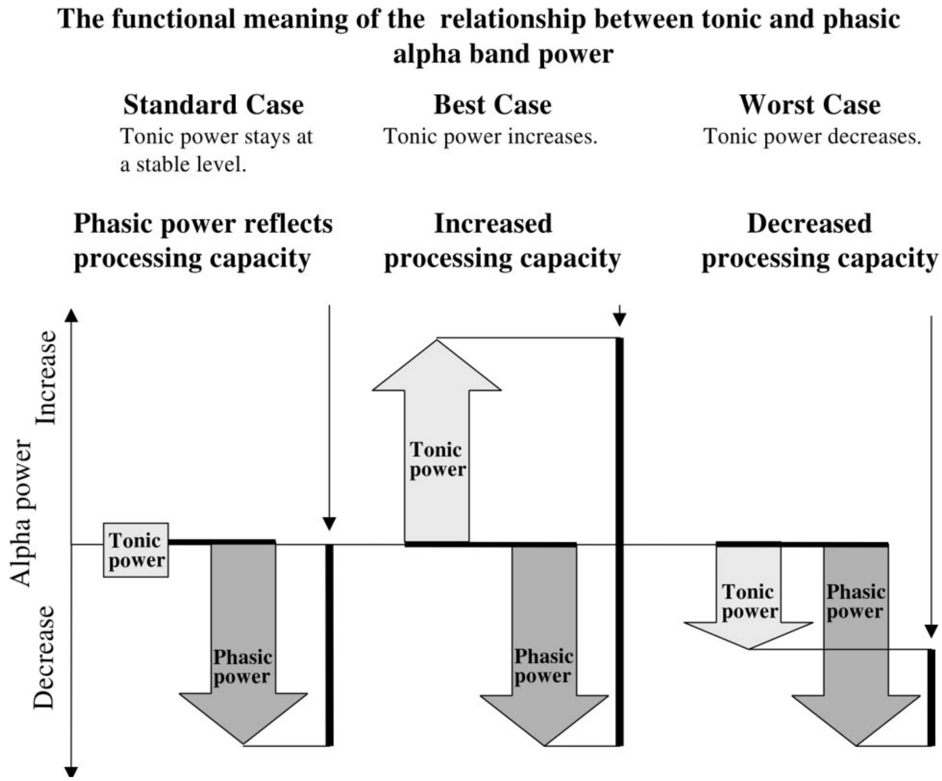

Fig. 1. The measurement and dissociation between tonic and phasic alpha power.

upper alpha power was observed, whereas during episodic retrieval, a significant increase in theta power developed. The conclusion from this study was that there is a dissociation between theta synchronization which is maximal during the processing of new information and upper alpha desynchronization which is maximal during retrieval and processing of semantic information. In a series of more recent experiments these findings could be replicated (e.g. see Klimesch et al., 1997a,b; Klimesch, 1999 for a review).

It is well known and was repeatedly shown that the alpha rhythm is sensitive to attentional demands (Ray and Cole 1985; Mulholland 1969). However, findings from our laboratory suggest that it is particularly the lower alpha band which is responsible for this observation. Cognitive theories of attention distinguish between two basic aspects, divided attention and selective attention (for a review see, e.g. Cowan 1988; Kahneman and Treisman, 1984). Both aspects refer to a subject' s processing capacity and to the question to what extent different tasks draw on the limited attentional resources.

The hypothesis that the lower alpha band reflects attention was supported by a variety of experiments (e.g. Klimesch et al., 1992; 1998a). In a study by Klimesch et al. (1993), we have found that good as compared to bad memory performers exhibit a significantly stronger desynchronization during encoding and retrieval in the lower alpha band (for similar results see also Sterman et al., 1996). We have interpreted these findings by assuming that good memory performance may be due at least in part by an increase in attention which is reflected by a strong desynchronization in the lower alpha band. Thus, a phasic response in the lower alpha band may be related to a subjects attempt to access attentional resources. In good agreement with the suggested interpretation Crawford et al. (1995) reported that low sustained attention subjects which have difficulty inhibiting distracting environmental stimuli have significantly more tonic lower alpha power than subjects not reporting attentional deficits.

Task related differences in alpha desynchronization may be ambiguous because tonic power influences the extent of a phasic response as the black bars in Fig. 1 illustrate. In a recent review (Klimesch, 1999) it was demonstrated that tonic alpha power is increased under conditions that are associated, with enhanced cognitive processing capacity or situations where subjects try to increase their capacity (e.g. during states of increased attention or in young healthy as compared to elderly subjects), but is decreased under conditions that are associated with reduced capacity (in neurological diseases, during drowsiness and sleep onset). In a similar way as for the theta band, we may distinguish a 'best case' from a 'worst case'. The best case is characterized by an increase, the 'worst case' by a decrease in tonic power. It should be noted that the 3 cases described for the alpha frequency band in Fig. 1 are comparable to the respective cases for the theta band (cf. Fig. 1 in the companion paper) with the exception that the direction of a phasic or tonic change goes into the opposite direction. Nonetheless, if we assume again 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.

In the present study, we analyzed the EEG in 4 different frequency bands of 2 Hz width, in the lower alpha, upper alpha, beta-1a and beta-1b band, spanning a frequency range of about 8–16 Hz (cf. Section 2 for details and the individual adjustment of frequency bands). Phasic alpha and beta is measured in terms of a change in event related band power (ERBP) during the poststimulus period with respect to the reference interval (Klimesch et al., 1998b; Figs. 1 and 2 and Section 2). Tonic power is measured in terms of alpha and beta band power during a reference interval preceding the presentation of an item (Fig. 1). The same sample of dyslexic and control subjects and the same tasks (reading of numbers, words and pseudowords) were analyzed as described in our companion paper.

It should be noted that in contrast to 'ERBP', the 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 7.5–12.5 Hz fulfils this requirement, it is recommendable to use a more neutral term, if frequency bands outside alpha or subbands within the broad alpha band are analyzed. Even in the latter case there usually are not separate peaks for, e.g. the lower and upper alpha band.

The basic predictions are based on our previous findings about the functional specificity of the upper and lower alpha band. With respect to the upper alpha band we assume that due to difficulties in word encoding, dyslexics may also have difficulties to extract the meaning of a word. If this is true, we expect larger tonic but smaller phasic upper alpha power particularly for frontal sites, which play an important

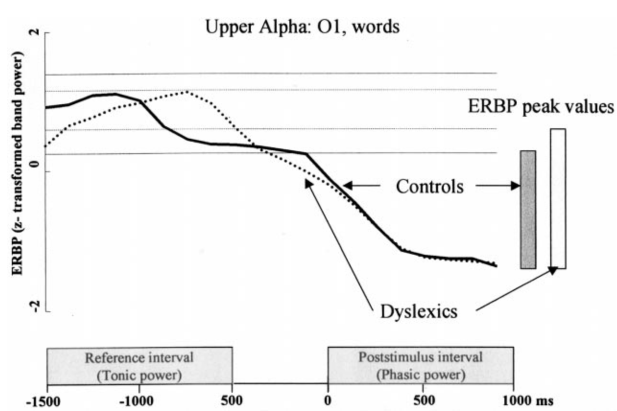

Fig. 2. An example showing a phasic band power change as measured by ERBP in the upper alpha band (cf. Section 2). ERBP peak values are indicated by grey bars and were used for plotting the results in Figs. 3–6. They are defined as the maximal phasic response (measured in z-units) exceeding the lower confidence interval.

role for the semantic encoding of words. Because pseudowords lack semantic information, we expect a lack of desynchronization during pseudoword encoding. Petersen et al. (1988) have shown that semantic task demands (particularly the retrieval of semantic information) are associated with a pronounced increase in the blood flow of left prefrontal regions (see also Raichle, 1993 and the review of related findings in Tulving et al., 1994). In addition, Martin et al. (1996) have found that naming pictures was associated with bilateral activation of the temporal lobes and the calcarine region, the left thalamus and the left anterior insula/inferior frontal region (Fig. 1 in Martin et al., 1996).

For the lower alpha band – reflecting attentional processes – we expect that dyslexics try to focus their attention more on those tasks which are more difficult for them. Thus, they should exhibit desynchronization in the lower alpha band particularly during reading of words and pseudowords. For dyslexics we expect the 'worst case' particularly in these conditions. With respect to the two beta bands predictions are difficult to make because of inconsistent findings reported in the literature (Ackerman et al., 1998; Flynn et al., 1992; Galin et al., 1988; Harmony et al., 1995; Marosi et al., 1995; Ortiz et al., 1992; Rippon and Brunswick, 1998, 2000; Rumsey et al., 1989).

In contrast to theta – which shows an event-related increase in band power – during alpha desynchronization there is no contribution to evoked activity which can be observed in event-related potentials (ERP's). Of course, this does not mean that ERP's do not show a frequency characteristic that lies in the alpha frequency range (Basar, 1999). The fact is that during maximal desynchronization - which we analyze in this study (cf. Fig. 2 for an illustration) - and which takes place at about 300–500 ms poststimulus (depending on the type of task) evoked alpha activity is lacking. During early poststimulus processes (of about 100–200 ms) when the extent of desynchronization is still small, evoked alpha activity may be quite large (Basar, 1999; Klimesch et al., 2000a,b). For these reasons, we do not measure evoked and induced activity separately as we have done for the theta band in the companion paper.

The EEG analysis focuses on two different aspects on (i) the phasic band power response during reading, and (ii) a task related change in tonic power during the reference period. The phasic response to a stimulus (number, word or pseudoword) is measured by calculating the significance of a band power change in relation to a reference interval preceding the presentation of a stimulus. Tonic changes are calculated by comparing (absolute) band power during the reference interval between task conditions (pronouncing numbers, words or pseudowords).

To our knowledge, there are no EEG studies analyzing phasic band power changes in dyslexic subjects. Thus, additional predictions for the present study – going beyond those already described above – are difficult to make on the basis of experiments which analyzed more global frequency specific EEG parameters in dyslexic subjects.

2. Methods

2.1. Subjects, material, apparatus and EEG recording

For a description see the respective sections of the companion paper.

2.2. The calculation of event-related (phasic) and tonic band power (ERBP)

In using alpha frequency AF(i) for each group of subjects i as cut off point between the two alpha bands, we distinguish between a lower, AF(i) to AF(i) − 2 Hz, an upper alpha band AF(i) to AF(i) + 2 Hz, and two beta bands, beta-1a AF(i) + 2 Hz to AF(i) +4 Hz, beta-1b AF(i) + 4 Hz to AF(i) +6 Hz. Averaged over the sample of subjects peak alpha frequency was 9.75 Hz. The description of the procedure to calculate ERBP and tonic (log) power is described in the companion paper and will not be repeated here (Klimesch et al., 1998b).

2.3. Statistical analyses and dependent variables

As described in the companion paper, for ERBP confidence intervals were calculated. The data depicted in Figs. 3–6 are the maximal values of ERBP exceeding the lower confidence limit as indicated by Fig. 2.

Again, ANOVAs with the same factors (GROUP, LOCATION and TASK) were calculated to evaluate differences in tonic band power. Because we are primarily interested in task- and group-related influences on tonic power, significant findings are reported only for factor TASK (and any interaction in which this factor is involved) and GROUP. 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.

3. Results

3.1. Phasic lower alpha

The number of significant band power changes is strikingly different between groups (36 for controls and 18 for dyslexics; cf. Fig. 3). As the result of a χ^2-test shows, the number of band power changes is significantly larger for controls than dyslexics. ($\chi^2(\text{d.f.} = 1) = 6.00$, $P < 0.02$).

3.2. Tonic lower alpha

Factor TASK, which is significant at centroparietal and occipital sites ($F(2, 28) = 3.61$, $P < 0.04$; $F(2, 28) = 4.26$; $P < 0.03$) reveals a strong influence of task difficulty particularly at O1 and O2 where pseudowords tend to have the smallest and numbers the largest power. When considering the extent of a phasic change, controls show a worst case for pseudowords at O2, whereas dyslexics show a worst case at O1 for words. Best cases can be observed for numbers at O2 for both groups. Factor GROUP did not reach significance.

3.3. Phasic upper alpha

An example of the time course of changes in upper alpha ERBP is shown in Fig. 2. Large negative z-values (scaled downwards) reflecting the extent of desynchronization can be observed particularly at O1 and O2 for both groups as Fig. 4 indicates.

In contrast to controls, who show a significant desynchronization in only 23 cases, dyslexics show a significant desynchronization in 40 (out of the 45 possible) cases. The respective χ^2-value closely misses to reach significance at the 5%-level ($\chi^2(\text{d.f.} = 1) = 3.46$, $P < 0.065$). However, large group differences can be seen at frontal, frontocentral and central sites where dyslexics show a significant desynchronization in 20 (out of 24 possible) cases, whereas for controls only 6 significant cases can be observed. Most interestingly, 5 of these 6 cases reflect the processing of words. A χ^2-test calculated for these 8 anterior sites (Fz, F3, F4, FC5, FC6, Cz, C3, C4) yields a highly significant effect ($\chi^2(\text{d.f.} = 1) = 7.54$, $P < 0.01$), showing that the number of desynchronizations is smaller for controls.

3.4. Tonic upper alpha

At occipital sites factor TASK ($F(2, 28) = 5.41$, $P < 0.01$) reached significance, showing that compared to words and pseudowords, numbers have the largest power. A significant interaction between TASK and LOCATION ($F(2, 28) = 3.676$, $P < 0.05$) was obtained at frontocentral regions. It indicates that a task related decrease in power (with increasing task difficulty) can be observed at the right hemispheric site FC6. Factor GROUP reached significance at frontal and central sites ($F(1, 14) = 4.89$, $P < 0.04$; $F(1, 14) = 4.47$, $P < 0.05$). At all of the respective leads upper alpha power is larger for dyslexics than controls.

Combinations of maximal desynchronization and maximal tonic power (‘best case’) can be observed for both groups at O2 and for numbers. A worst case (minimal desynchronization together with minimal tonic power) can be observed for pseudowords at O2 but for controls only.

3.5. Phasic beta-1a

The number of significant band power changes (desynchronization) is 19 for controls and 29 for dyslexics. The findings which are summarized in Fig. 5 reveal a strong frontal, right central and centroparietal pseudoword effect for dyslexics.

3.6. Tonic beta-1a

None of the variance sources involving factor TASK or GROUP reached significance.

3.7. Phasic beta-1b

For the beta-1b band, 20 significant band power changes (desynchronization) were obtained for controls and 21 for dyslexics. The findings are summarized in Fig. 6 and show a strong task specific effect that distinguishes both groups. In contrast to dyslexics, controls show a selective desynchronization for numbers at all midline and right hemispheric recording sites, whereas at left hemispheric sites a selective desynchronization for words can be observed.

3.8. Tonic beta-1b

A main effect for TASK ($F(2,28) = 4.83$, $P < 0.02$) was found at frontal sites. The respective means show a task related decrease in power with increasing task difficulty. For central, centroparietal, parietal and occipital sites the interaction GROUP × TASK reached significance ($F(2,28) = 5.91$, $P < 0.01$; $F(2,28) = 5.89$, $P < 0.01$; $F(2,28) = 4.62$, $P < 0.03$; $F(2,28) = 3.304$, $P < 0.05$). For controls and all respective recording sites, tonic power is larger for numbers and words as compared to pseudowords, whereas for dyslexics the opposite tendency could be observed. In this group tonic power for pseudowords tends to be larger at most recording sites. The respective 'worst' and 'best' cases are depicted in Fig. 6. Factor GROUP did not reach significance.

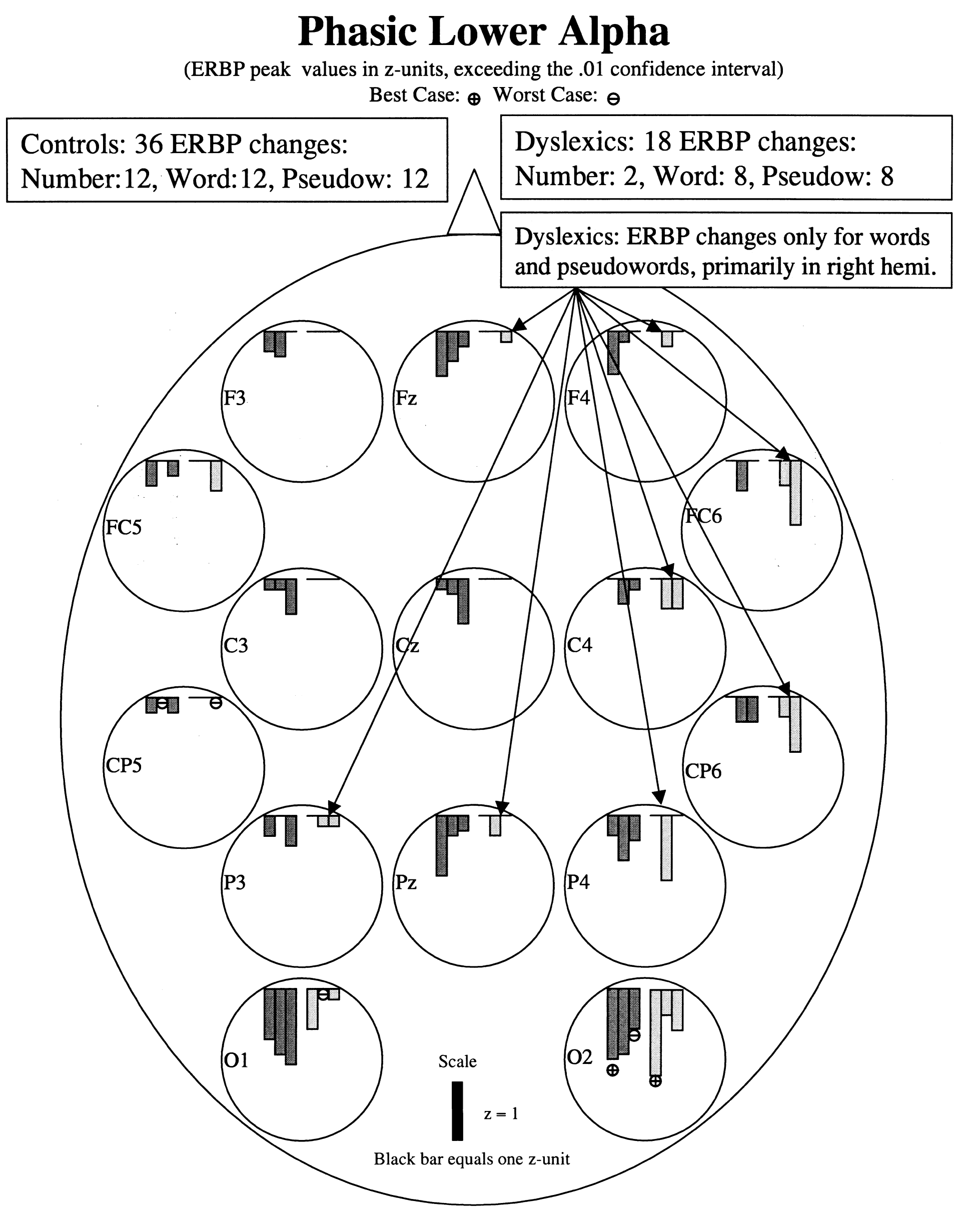

Fig. 3. The results for the lower alpha band. At each recording site, 3 bars are plotted. Dark grey bars reflect the findings for the control group, light grey bars those for dyslexics. From left to right (for each group and recording site), the first, second and third bar represent the mean ERBP peak values (cf. Fig. 2) for the number, word and pseudoword task, respectively.

4. Discussion

The findings show again a frequency specific pattern of task and group differences. The most 'reactive' band with the largest number of significant phasic changes in band power is the upper alpha band. The most selective findings with respect to topographical and group differences, however, were obtained in the two beta bands.

In agreement with the predictions described in the Introduction, we see that for dyslexics lower alpha desynchronization can be observed primarily during reading of words and pseudowords. The only exceptions are O1 and O2, where desynchronization was found also for numbers. Most interestingly at O2 a 'best case' was observed for numbers, whereas at O1 a 'worst case' was obtained for words. These findings indicate that dyslexics increase their attention during the encoding of words and pseudowords. At occipital sites, they also succeed well to increase their attention during the encoding of numbers at O2 but fail for words at O1. Controls show a completely different and more diffuse pattern of phasic band power changes with respect to topography and task condition. This is in strong agreement with other findings from our laboratory which indicate that the lower alpha band responds topographically widespread and rather diffusely. The conclusion for the lower alpha band is that dyslexics concentrate more on words and pseudowords, whereas controls exhibit a very distributed pattern of desynchronization. Furthermore,

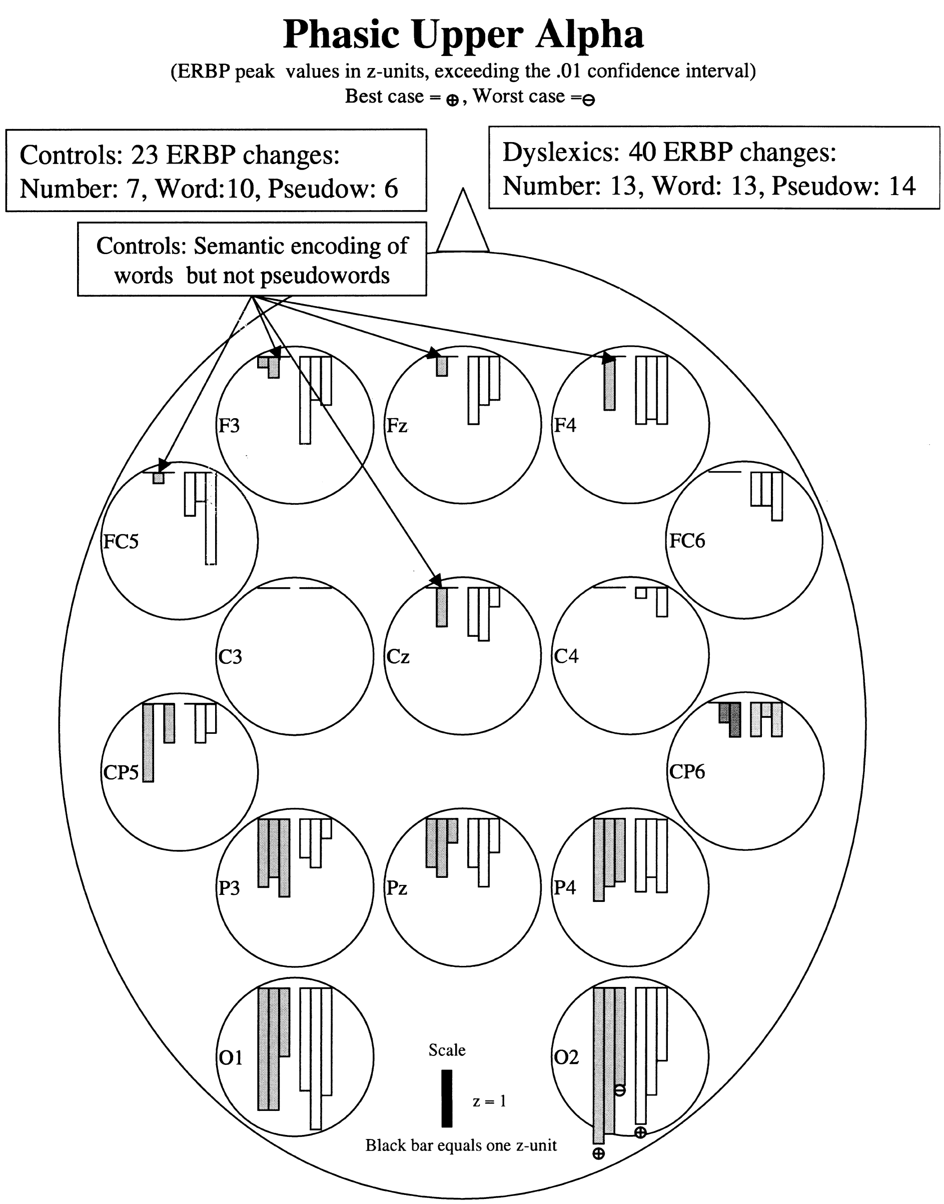

Fig. 4. The results for the upper alpha band.

whereas both groups do well for the encoding of numbers (right hemisphere encoding at O2) dyslexics show a complete lack of attentional control during word encoding at the respective left hemispehric site O1.

We have expected that dyslexics (because of their deficit in word encoding) may have a 'chronic' difficulty to extract the meaning from words and, thus, may have a larger tonic upper alpha power than controls. This prediction is supported. Our findings indicate that dyslexics have significantly larger upper alpha power at frontal and central sites, where semantic encoding is known to play an important role. This effect is mirrored by a larger event-related decrease in power (desynchronization) for dyslexics at these sites which is non-selective with respect to task conditions. In addition, they show a larger number of significant desynchronizations at anterior sites. Controls, however, exhibit a highly selective semantic word effect at left frontocentral sites (as can be expected from PET- or fMRI-studies, e.g. Petersen et al., 1988; Martin et al., 1996; Raichle, 1993 and the review in Tulving et al., 1994). At Fz, F4, FC5, Cz and (with a minor exception) at F3 only words elicit a significant desynchronization. Since absolute power is significantly lower in controls, this finding reflects an extremely high selectivity for semantic word encoding. 'Best cases' can be observed for both groups for the encoding of numbers at O2 which reflects the intact ability of dyslexics to encode numbers (cf. the similar findings for the lower alpha band). A 'worst case' can be observed for controls and pseudowords at 02, which possibly reflects the primarily left hemispheric attempt of semantic pseudoword

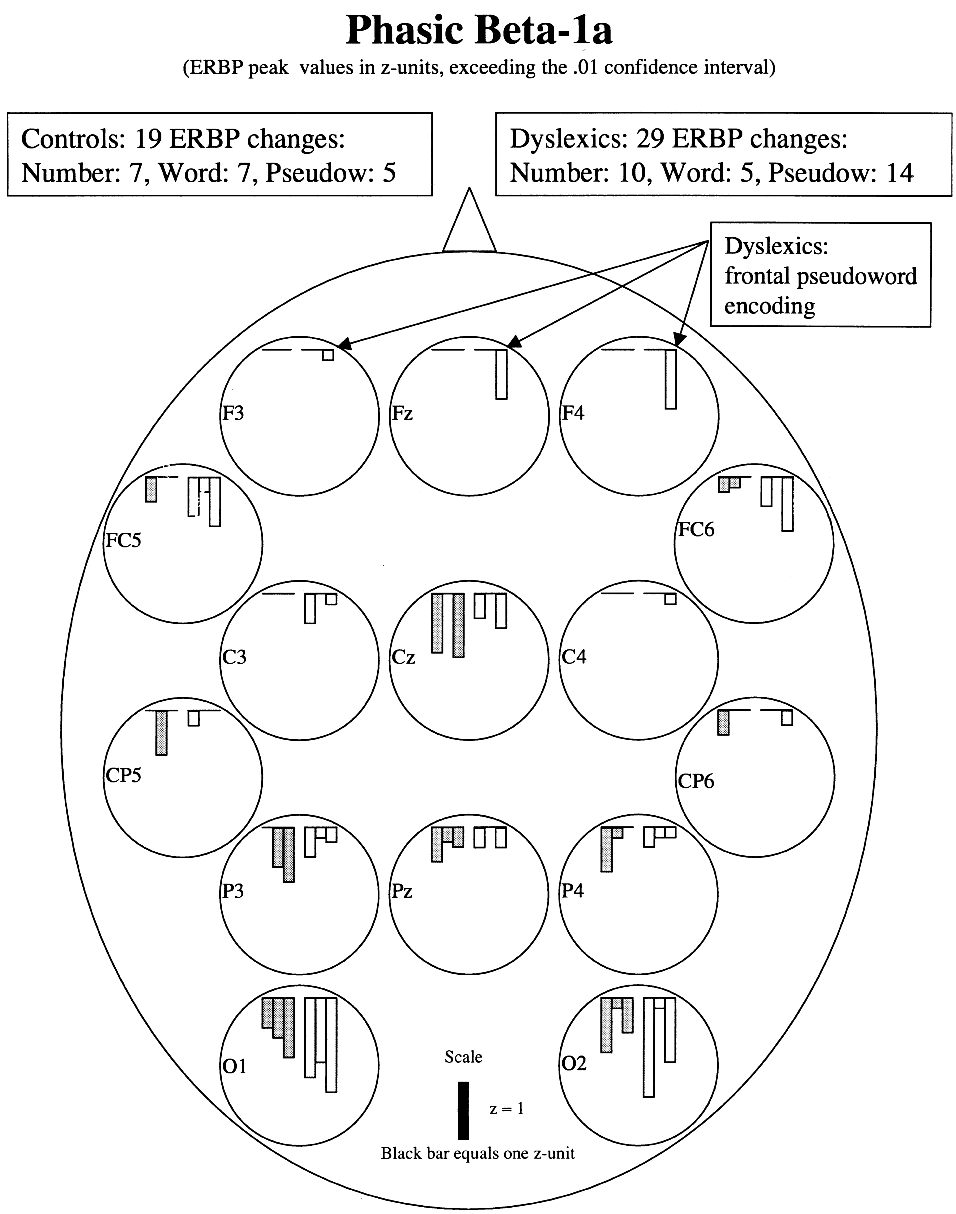

Fig. 5. The results for the beta-1a band.

encoding at O1. The conclusions are that at anterior sites, dyslexics show a topographically widespread increase in upper alpha power reflecting an attempt to increase semantic processing resources. This interpretation is also supported by the findings in the lower alpha band which show an increase in attention at frontal and other right hemispheric regions. Controls, on the other hand, show a high processing selectivity at anterior sites, possibly reflecting high processing efficiency for semantic word encoding.

The beta-1a band reveals a selective 'deficit' for the processing of words in dyslexics. In this group only 17% of all significant band power changes are due to the processing of words as compared to 36% for controls. Most interestingly, at frontal sites, significant findings were obtained only for pseudowords and dyslexic subjects. The functional meaning of this frequency band is difficult to interpret. Given the fact that dyslexics show a larger number of significant findings, which in addition can be observed primarily for pseudowords, we may assume that the beta-1a band reflects cognitive processes (or encoding strategies) which are related to the processing of non-words.

The beta-1b band shows a highly selective pattern of phasic band power changes for the processing of numbers and words in controls. Whereas words are processed in the left hemisphere particularly at FC5, CP5 and P3 (cf. Fig. 6), numbers are processed in the right hemisphere (e.g. Dehaene, 1996) and at midline sites. Because, numbers and words show large tonic power (as compared to pseudo-

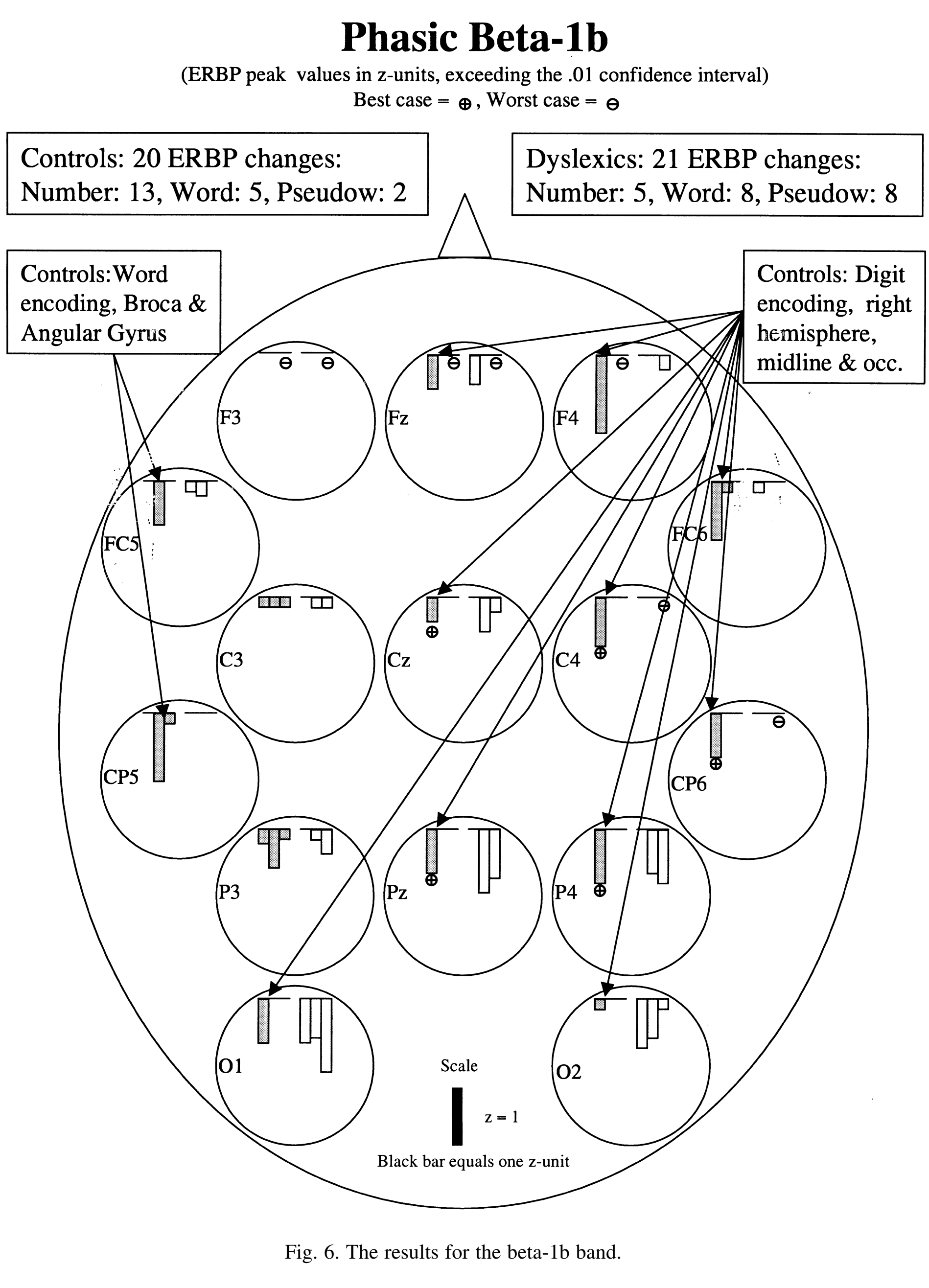

Fig. 6. The results for the beta-1b band.

words), we observe many 'best cases' (particularly for numbers) with high topographic selectivity. Dyslexics show a strikingly different pattern of results with a lack of task selectivity. Whereas at occipital sites significant desynchronization can be observed in response to numbers, words and pseudowords. At parietal and central locations only words and pseudowords elicit a phasic response. The conclusion appears straight forward. The beta-1b band reflects the processing capacity and selectivity for words and numbers which is reduced in dyslexics. Most interestingly, selective word processing in controls is associated with those recording sites which correspond to Broca's area (FC5) and the angular gyrus (CP5, P3). We may conclude that the beta-1b obviously reflects the graphemic-phonetic encoding of words but in controls only.

The general conclusion regarding processing deficits in dyslexics is based on the following findings. (i) A lack of pseudoword encoding into (visual) working memory at O1 and O2 and possibly a more general difficulty to encode items into working memory as indicated by an attenuated phasic theta response at frontal sites (cf. the results reported in our companion paper). (ii) A lack of attentional control as indicated by a significantly smaller number of desynchronizations in the lower alpha band and a 'worst case' during word encoding at O1. (iii) A lack of selective semantic word encoding as indicated by a consistent significant frontal upper alpha desynchronization under all of the 3 task conditions. (iv) A lack of a selective topographic pattern for the processing of words and numbers (cf. the results for the beta-1b band in Fig. 6).

A comparison of the findings between the frequency bands reveals an aspect which is of general interest. Comparing the upper theta with the lower alpha band indicates the sharp transition from synchronization (band power changes scaled upwards) to desynchronization (band power changes scaled downwards). This finding underlines the importance of the use of rather narrow and adjusted frequency bands. If the frequency ranges of these bands would overlap, the effects of synchronization and desynchronization would cancel each other. The use of broad and fixed frequency bands may very well be responsible for the inconsistent results reported in the literature.

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