Cortical Processing of Vowels and Tones as Measured by Event-Related Desynchronization

Christina M. Krause[*][□], Heikki Lang[+][□], Matti Laine[#][□], Mika Kuusisto[□], and Bodil Pörn[□][†]

Summary: Event-Related Desynchronization (ERD) and Synchronization (ERS) were studied in 20 normal subjects during a Sternberg-type auditory memory-scanning paradigm. Half of the subjects performed the experiment with vowels and the other half with tones as stimuli. The stimuli consisted of 100 msec long synthesized vowels and 100 msec long tones produced by eight different synthesized instruments. In this paradigm each trial started with the presentation of a visual warning signal, after which a four-stimulus set was presented for memorization whereafter a probe stimulus was presented and identified by the subject as belonging or not belonging to the memorized set. The ERD/ERS of the lower (8 - 10 Hz) and upper (10 - 12 Hz) alpha frequency bands differed in their reactivity to stimulus type; the differences between the two frequency bands reached statistical significance only in the case of vowels. The presentation of the memory set elicited ERS which was more pronounced in the 10 - 12 Hz frequency band and greater for vowels than for tones. On the other hand, the presentation of the probe elicited ERD which was greater for vowels than for tones, especially in the upper alpha frequency band. The results of this exploratory study suggest that ERD is closely related to memory processes and that the ERD/ERS-technique might provide a valuable tool for future reseach encompassing more complex auditory stimulation like speech and music.

Key words: Event-related desynchronization; Event-related synchronization; Memory; Alpha frequency band; Vowels; Tones.

Introduction

Event-Related Desynchronization (ERD) is the amount of event-related decrease in the on-going electric activity of the brain (Pfurtscheller 1977; Pfurtscheller and Aranibar 1977). ERD of the alpha frequency band has been observed in association with visual (Pfurtscheller and Aranibar 1977; Aranibar and Pfurtscheller 1978; Pfurtscheller, Steffan and Maresch 1988; Pfurtscheller and Klimesch 1991) and auditory (Krause et al. 1994; Schulter, Kreutzhaler and Pfurtscheller 1990) stimulation, during voluntary movement tasks (Pfurtscheller and Aranibar 1979; Pfurtscheller and Neuper 1992) as well as during cognitive and attentional tasks (Klimesch et al. 1988; Van Winsum et al. 1984; Klimesch et al. 1990; Klimesch et al. 1992; Klimesch et al. 1993; Dujardin et al. 1993).

Different frequency ranges within the alpha band have been claimed to reflect different neuronal processes. The ERD of the lower alpha frequencies (8-10 Hz) is topographically more widespread, longer-lasting and appears to represent cortical correlates of attentional and motivational processes. On the other hand, the ERD of the upper alpha frequencies (10-12 Hz) has been reported to be topographically more restricted and to reflect stimulus-related processes (Pfurtscheller et al. 1988; Klimesch et al. 1992; Pfurtscheller and Klimesch 1992a and b).

The opposite phenomenon to ERD, Event-Related Synchronization (ERS), is the amplitude enhancement of brain electric activity and indicates cortical areas at rest or in an idling state (Pfurtscheller 1992; Pfurtscheller and Klimesch 1992a).

ERD maps represent the topographical and temporal distribution of alpha desynchronization (Pfurtscheller 1989). ERD maps can be used to investigate cortical activation patterns in time and space (Pfurtscheller et al. 1988; Pfurtscheller and Klimesch 1990; Pfurtscheller et al. 1991).

In earlier investigations on ERD and ERS in the auditory stimulus modality (Krause et al. 1994), we have observed similar differences between the ERD/ERS of

---

[*] Academy of Finland and Department of Psychology, Åbo Akademi University, Finland.

[+] Department of Clinical Neurophysiology, University of Turku, Finland.

[#] Department of Neurology, University of Turku, Finland.

[□] Centre for Cognitive Neuroscience, University of Turku, Finland.

[‡] Department of Statistics, Åbo Akademi University, Finland.

Accepted for publication: May 9, 1995.

This study was financially supported by the Council for Social Sciences, Academy of Finland (project 7338).

Correspondence and reprint requests should be addressed to Christina Krause, Department of Psychology, Åbo Akademi University, FIN-20500 Turku, Finland.

email: tkrause@aton.abo.fi.

fax: 358-21-2654833

the lower and upper alpha frequency bands as have been repeatedly reported by Pfurtscheller and his co-workers in their studies on ERD in the visual stimulus modality (Pfurtscheller et al. 1988; Pfurtscheller and Klimesch 1990; Klimesch et al. 1992).

A priori, it seems self-evident that after peripheral acoustic analysis, higher level processing of speech vs. music in the human brain must be different. Indeed, behavioral studies of brain-damaged individuals have shown that speech- vs. music-related functions can dissociate (e.g., Brust 1980). Another type of dissociation is provided by laterality research. Dichotic listening studies with normal right-handers have shown that a range of verbal materials produce a right ear advantage which is consistent with the clinically observed left hemisphere dominance for language. In contrast, the discrimination of the pitch of complex tones typically shows a left ear advantage (Sidtis 1981). Studies on the asymmetry of the ongoing EEG during listening to speech (Beaumont 1983) vs. music (Petsche et al. 1988) have also suggested processing differences between these two types of auditory stimuli. However, it is not known whether and how the ERD phenomenon would reflect this processing difference.

In the present exploratory study, speech- vs. music-related auditory stimuli were used. The choice of vowels vs. tones (musical timbre) allowed us to study and to compare brain processes associated with both speech- and music-related encoding and retrieval. Half of the subjects listened to synthetic vowels while the other half heard tones. The tones were synthesized with different instrument sounds and differed from each other concerning musical timbre. Perception of musical timbre should be a more adequate measure of music-related brain processes than e.g., perception of sine tone stimuli (Crummer et al. 1994). Any differences in the reactivity of ERD/ERS to these two auditory stimulus types could shed light in the ways speech vs. music are dealt with in the human brain.

We were also interested in whether the lower (8-10 Hz) vs. the upper (10-12 Hz) alpha frequencies would exhibit differential reactivity to stimulus type. In order to check and measure the subject's attentiveness to the auditory stimuli we chose to use a modified version of Sternberg's memory scanning paradigm (Sternberg 1966). In each trial the subjects listened to four auditory stimuli (memory set) which they were asked to retain in their memory. After several seconds a fifth auditory stimulus was presented (probe). The subjects then had to decide whether the probe belonged to the memorized set or not. The choice of this experimental paradigm allowed us also to examine any possible differences in ERD/ERS between encoding and retrieval from memory.

Materials and methods

Subjects

Subjects were 20 healthy, right-handed adult volunteers. Half of the subjects were males and half were females ranging in age from 22 to 46 years (mean=30.1, SD=7.1). The distribution of the genders was equal in all subpopulations studied in order to eliminate the effect of sex differences in the EEG (Petsche et al. 1988). The handedness of the subjects was verified with an unpublished Finnish version of the Boston V.A. Handedness Questionnaire. None of the subjects reported having any hearing defects, neurological disorders or being on medication. In addition, none of them had professional musical education and all were native speakers of Finnish.

Stimuli

The stimuli consisted of eight auditory synthesized vowels (/a/, /e/, /i/, /o/, /u/, /y/, /ä/, /ö/) and eight auditory tones synthesized by different instrument sounds (violin, drum, piano, bass, trumpet, flute, organ, marimba). The vowels were synthesized with a Dennis Klatt's KLSYN88 synthesizer and the instrument sounds were synthesized with a Roland SC-7 synthesizer. The stimuli were presented through E-A-R-TONE ABR insert earphones (10 Ω) at a comfortable sound pressure level (65 dB_{spl}).

The digitized stimuli were stored in the Neuroscan Stim sound file format. The Neuroscan Stim system was used to control the presentation of the auditory stimuli. Half of the subjects (5 males, 5 females) received vowels as stimuli and the other half (5 males, 5 females) tones. The stimuli were presented in 64 pseudorandomized four-stimulus blocks. The blocks were presented in random order. The length of a single auditory stimulus was 100 msec and the length of a four-stimulus memory set (ISI 500 ms from onset to onset) was 1600 ms. Three seconds after the presentation of the memory set, a fifth probe stimulus was presented to the subject. In 50% of the cases, the probe was among the previously presented four-stimulus block.

Procedure

Following electrode placement and instrument calibration, the subject was seated in a comfortable chair in a dimmed registration room and the experimental procedure was explained. To reduce muscle artefacts in the EEG signal, the subject was instructed to assume a comfortable position and to avoid movement. The subject was instructed to look at a TV screen placed 1.5 m in front of him or her and to avoid unnecessary eye move-

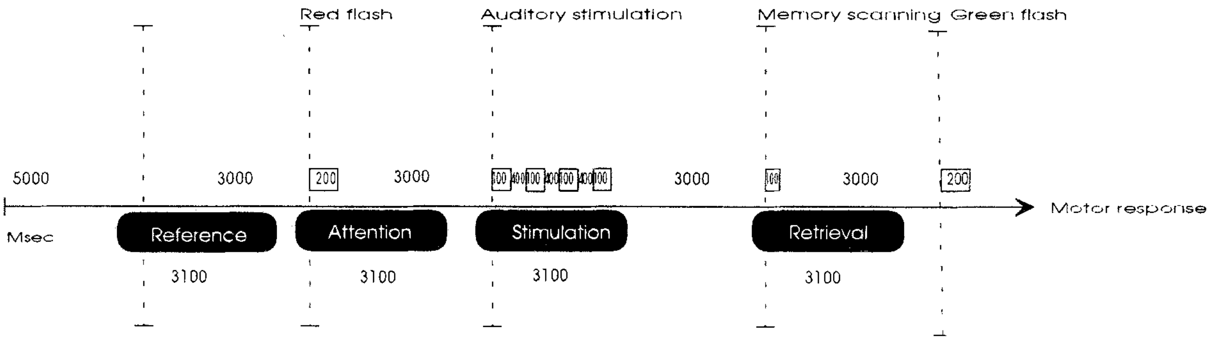

Figure 1. The experimental paradigm. Data segments used for classification (black areas) are: reference, visual warning signal, memory set and probe.

ments. The first 8000 msec of each trial was considered as an intraexperimental resting condition. The last 3100 msec of this epoch was used as an intraexperimental reference for the calculation of the ERD values. Subsequently, a visual warning signal (a red flash), appeared for 200 msec on the TV screen. After 3000 msec, a 1600 msec four-stimulus block was presented (memory set). Three seconds later, a fifth 100 msec stimulus (probe) was presented. The subject then had to decide whether or not the probe had been among the memorized set. In an attempt to avoid muscle artefacts and movement-related ERD, the subjects were asked to withhold their response until a visual warning signal (a green flash), would appear on the TV screen. Three seconds after the presentation of the probe, the green spot appeared, prompting the subject to respond by pressing either the "yes" or "no" button on a response pad. The following trial started 5000 msec after the subject had given an answer by means of the response pad. The experimental design is shown in figure 1. The length of a single trial was 19.2 seconds (+ response time) and the number of trials totaled 64.

Data collection

Twenty-two Ag/AgCl electrodes (Siemens-Elema) were placed bilaterally on the subject's scalp using electrode cream (Berner) and the 10/20 system of electrode placement. EOG-electrodes were sited on the outer side of the eyes and all electrodes were referred to linked ears.

EEG data were gathered while the subject was seated in a comfortable chair in an acoustically isolated, darkened recording room. Raw EEG signals were recorded using the Neuroscan 386 Scan 3.0 data acquisition system with a Braintronics CNV/ISO-1032 amplifier with a frequency band of 0.3 to 70 Hz. The impedance of recording electrodes was monitored for each subject with a Braintronics electrode impedance meter prior to data collection and it was always below 5 kΩ.

Data processing

The data processing was based on 64 trials of event-related EEG data with epochs of 3100 ms. The data was recorded using a sampling rate of 200 Hz making 620 samples for each epoch and channel. The data was then bandpass filtered with linear FIR (Finite Impulse Response) filters in the 8-10 Hz and 10-12 Hz frequency bands. The length of the filters was 129 points. In order to render a signal proportional to the power of the chosen alpha band, the filtered signal samples were squared and averaged over all 64 trials using a 100 msec time window.

A Fast Fourier Analysis was used to determine the amplitude spectrum in microvolts for the reference interval for each subject individually. From these spectra (electrode Pz) the frequency within the alpha band displaying the greatest amplitude (Individual Alpha Peak Frequency, IAPF) was computed for each subject.

Quantification of ERD

Event-synchronous EEG data was sampled, bandpass filtered and averaged across all trials. This resulted in an average power versus time curve. To obtain a normalized measure of the ERD, the mean power in the reference interval was set at 100% from which alpha power decrease (ERD) or increase (ERS) was determined in percentage. A time window of 250 msec was used in these calculations.

Statistical analyses

The first pre-stimulation 100 msec of each original 3100 msec epoch was excluded, leaving epochs of 3000 msec for the analyses. The statistical analyses were calculated using 12 time windows of 250 msec for each electrode and for each 3000 msec epoch.

The non-parametric Wilcoxon test for paired samples was used to evaluate the significance ($p<.05$, $p<.01$) of alpha power changes with respect to the reference (ERD-

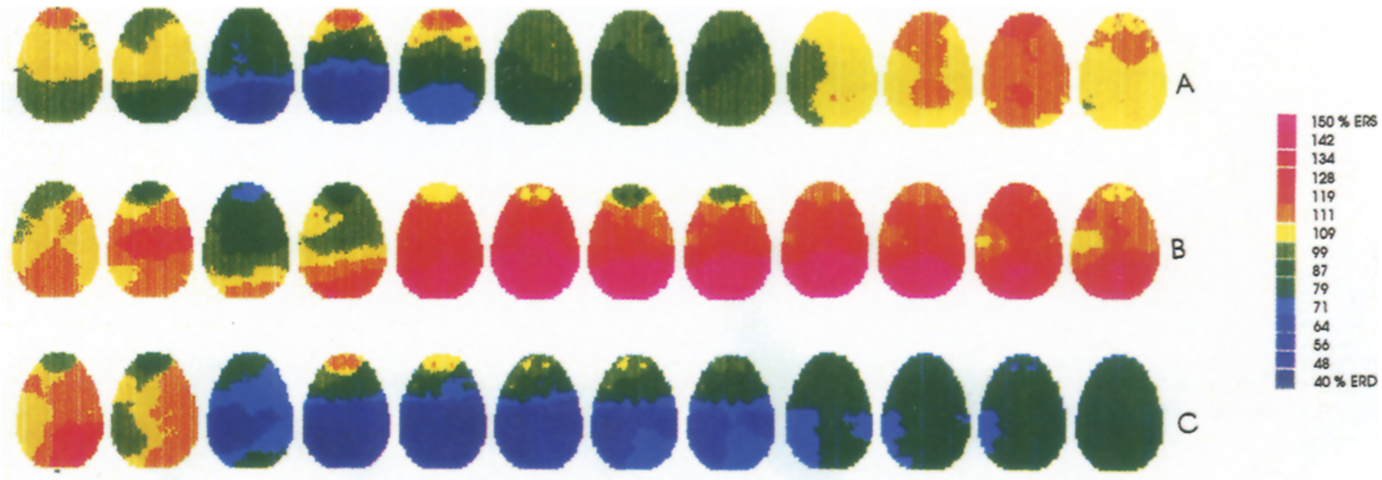

Figure 2. Series of grand average ERD maps calculated in the 8-10 Hz frequency band for VOWELS for each experimental condition: visual warning signal (A), memory set (B) and probe (C). Each row represents a 3000 msec epoch and each map represents a 250 msec time window. The ERD/ERS scale is from 40% to 150%. "Cold" colors denote areas with greatest alpha desynchronization (power decrease) whereas "hot" colors signify areas with greatest alpha synchronization.

values) for each experimental condition. These analyses were performed separately for the two stimulation types for the 8-10 and 10-12 Hz frequency bands. The same non-parametric test was used to determine the significance of any differences between the 8-10 and 10-12 Hz frequency bands separately for both stimulation groups. The Mann-Whitney U Test was used to determine the significance ($p<.05$, $p<.01$) of any differences between the two stimulation types separately for both alpha frequency bands. The t-test for equality of means was used to evaluate the significance of any differences between the two groups on the mean percentage correct answers, IAPF and its amplitude.

The results were displayed as 12 grand average ERD maps of 250 msec for each 3000 msec epoch for each experimental condition (attention, auditory stimulation, memory retrieval) for the lower (8-10 Hz) and the upper (10-12 Hz) frequency band. The statistical significance of the differences between frequency bands and stimulation types was displayed as 12 probability maps of 250 msec for the 3000 msec epochs for each experimental condition and for each electrode.

Results

All the subjects performed well in the memory task, indicating that they had listened to the stimuli attentively. The mean percentage of correct answers for the group receiving vowels was 87.5% (SD=6.8) and 79.9% (SD=7.9) for the group receiving tones. The difference between the two groups reached statistical significance ($t(18)=-2.31$, $p=.033$).

The mean IAPF for the group receiving vowels was 9.5 Hz (SD=.85) and 9.3 Hz (SD=1.34) for the group receiving tones. This difference between the groups was not significant ($t(18)=.40$, $p=.695$). The mean amplitude of the IAPF for the group receiving vowels was 7.98 μV (SD=5.95) and 6.08 μV (SD=5.66) for the group receiving tones. There were no significant differences between the groups concerning the amplitude of the IAPF ($t(18)=.73$, $p=.474$).

1. Results from the 8-10 Hz frequency band.

Vowels (figure 2). The presentation of the visual warning signal elicited a significant ($p<.01$) parieto-occipital ERD of 56% starting at 500 msec after the presentation of the red flash on the TV monitor. The presentation of the memory set elicited a significant ($p<.01$) ERS of 150% in the parietal and occipital electrodes at 1250 - 2500 msec. The presentation of the probe elicited a significant ($p<.01$) ERD of 56% in the occipital, parietal and central electrodes at 500 - 2500 msec after the presentation of the probe vowel.

Tones (figure 3). The presentation of the visual warning signal elicited a significant ($p<.01$) occipital ERD of 64% starting at 750 msec after the presentation of the red flash on the TV monitor. The presentation of the memory set elicited a significant ($p<.01$) ERD of 80% in the occipital and central electrodes at 750 - 1000 msec and a significant ERS of 130% at 1750 - 2250 msec in the cental electrodes. The presentation of the probe elicited a significant ($p<.01$) ERS of 130% at 250 - 500 msec in the frontal electrodes and a significant ($p<.01$) ERD of 64% in the central and temporal electrodes at 750 - 1250 msec after the presentation of the probe tone.

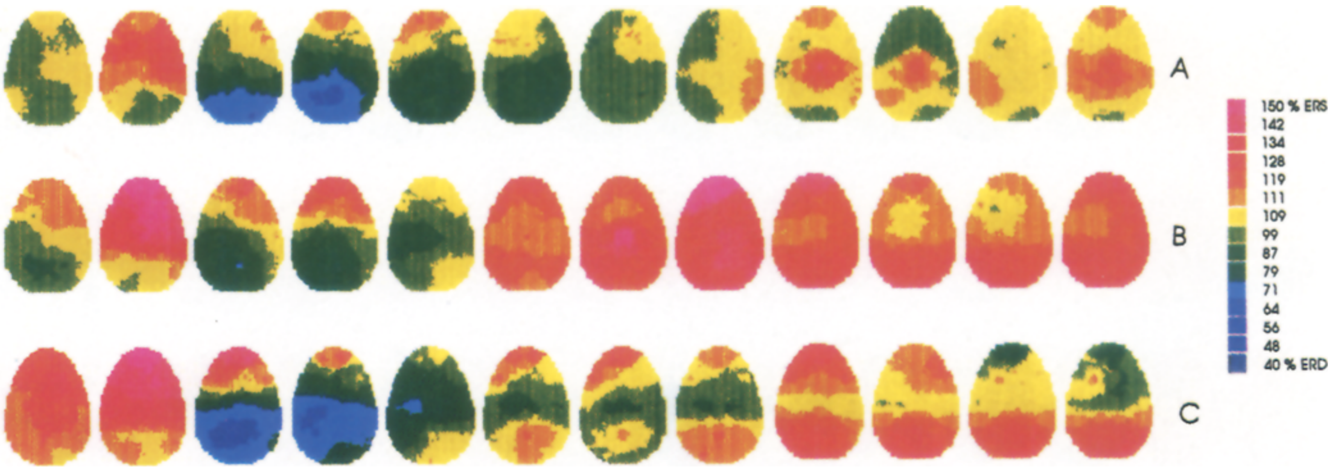

Figure 3. Series of grand average ERD maps calculated in the 8-10 Hz frequency band for TONES for each experimental condition: visual warning signal (A), memory set (B) and probe (C). Each row represents a 3000 msec epoch and each map represents a 250 msec time window. The ERD/ERS scale is from 40% to 150%. "Cold" colors denote areas with greatest alpha desynchronization (power decrease) whereas "hot" colors signify areas with greatest alpha synchronization.

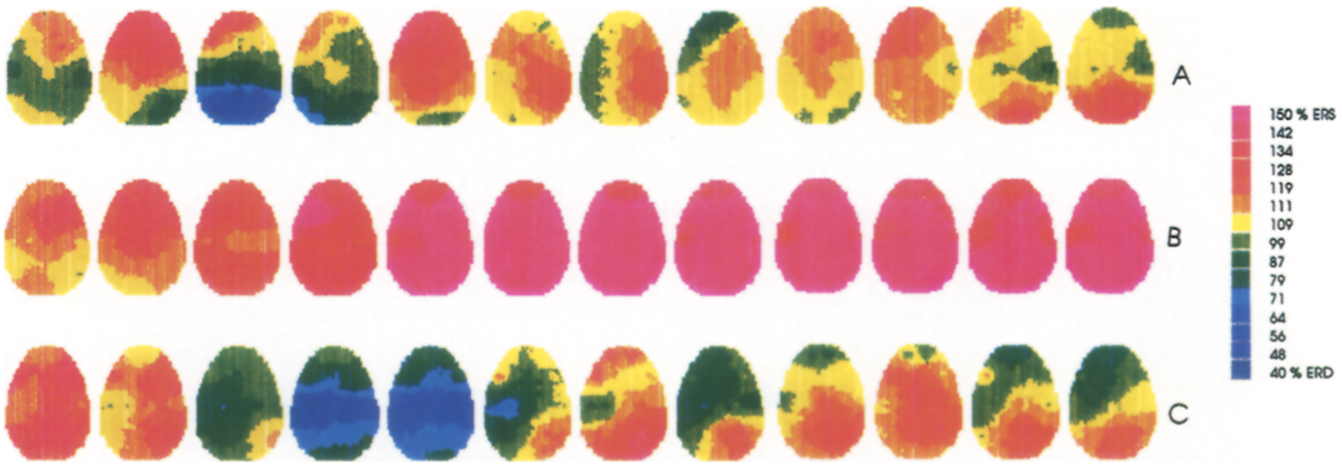

Figure 4. Series of grand average ERD maps calculated in the 10-12 Hz frequency band for VOWELS for each experimental condition: visual warning signal (A), memory set (B) and probe (C). Each row represents a 3000 msec epoch and each map represents a 250 msec time window. The ERD/ERS scale is from 40% to 150%. "Cold" colors denote areas with greatest alpha desynchronization (power decrease) whereas "hot" colors signify areas with greatest alpha synchronization.

2. Results from the 10-12 Hz frequency band.

Vowels (figure 4). The presentation of the visual warning signal elicited a significant (p<.01) parieto-occipital ERD of 56% starting at 500 msec after the presentation of the red flash on the TV monitor. The presentation of the memory set elicited a significant (p<.01) ERS of 150% at 750 - 3000 msec. The presentation of the probe elicited a significant (p<.01) ERD of 56% in the central and temporal electrodes at 750 - 1500 msec after the presentation of the probe vowel.

Tones (figure 5). The occipital ERD of 80% starting at 500 msec after the presentation of the visual warning signal on the TV monitor failed to reach the level of significance. The presentation of the memory set elicited a significant (p<.01) ERS of 120% in the frontal electrodes at 250 - 500 msec and of 150% in the central and temporal electrodes at 1500 - 2000 msec. The presentation of the probe elicited a significant (p<.01) ERS of 130% at 250 - 500 msec in the frontal electrodes and a significant (p<.01) ERD of 70% in the central and temporal electrodes at 750 - 1750 msec after the presentation of the probe tone.

Figure 5. Series of grand average ERD maps calculated in the 10-12 Hz frequency band for TONES for each experimental condition: visual warning signal (A), memory set (B) and probe (C). Each row represents a 3000 msec epoch and each map represents a 250 msec time window. The ERD/ERS scale is from 40% to 150%. "Cold" colors denote areas with greatest alpha desynchronization (power decrease) whereas "hot" colors signify areas with greatest alpha synchronization.

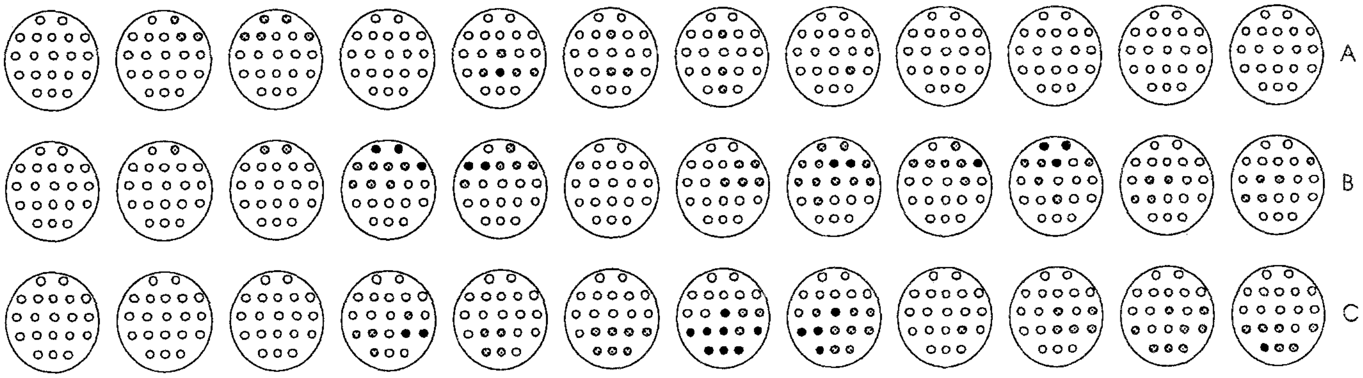

Figure 6. Serial probability maps calculated for each experimental condition: visual warning signal (A), memory set (B) and probe (C) displaying the significance of any differences between the lower (8-10 Hz) and upper (10-12 Hz) alpha frequency bands for VOWELS for each electrode. Each row represents a 3000 msec epoch and each map represents a 250 msec time window. Solid circles p<0.01, dot within circle p<0.05.

3. Differences between the 8-10 and 10-12 Hz frequency bands for vowels and tones.

Vowels (figure 6). After the presentation of the visual warning signal, the ERD/ERS of the lower and upper alpha frequency bands differed significantly (p<.05) at 250 - 750 msec and at 1000 - 2000 msec due to the fact that the occipital ERD of the 8-10 Hz frequency band was more widespread and longer lasting than that of the 10-12 Hz frequency band. After the presentation of the memory set, the frequency bands differed significantly (p<.01) at 500 - 1250 msec and at 1500 - 3000 msec. These differences were due to the fact that the ERS elicited in the 10-12 Hz alpha frequency band was more widespread and longer lasting than that of the lower alpha frequency band. After the presentation of the probe vowel, the frequency bands differed significantly (p<.01) at 750 - 3000 msec. This is explained by the fact that the ERD elicited by the probe was more widespread and longer lasting in the 8-10 Hz frequency band.

Tones (figure 7). After the presentation of the visual warning signal, the ERD/ERS of the lower and upper alpha frequency bands differed significantly (p<.05) at 750 - 1750 msec due to the fact that the occipital ERD of the 8-10 Hz frequency band was more widespread and longer lasting than that of the 10-12 Hz frequency band. After the presentation of the memory set, the alpha frequency bands differed significantly (p<.01) at 750 - 1000

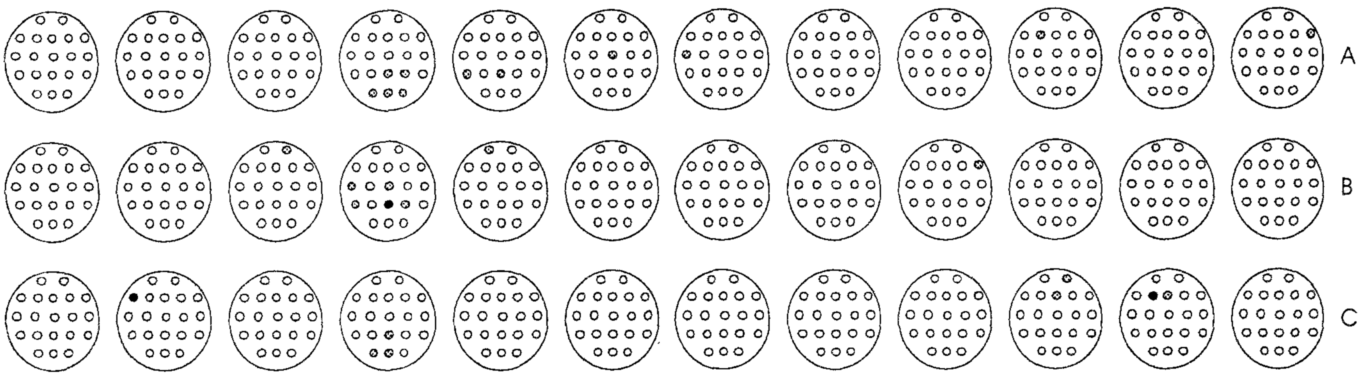

Figure 7. Serial probability maps calculated for each experimental condition: visual warning signal (A), memory set (B) and probe (C) displaying the significance of any differences between the lower (8-10 Hz) and upper (10-12 Hz) alpha frequency bands for TONES for each electrode. Each row represents a 3000 msec epoch and each map represents a 250 msec time window. Solid circles p<0.01, dot within circle p<0.05.

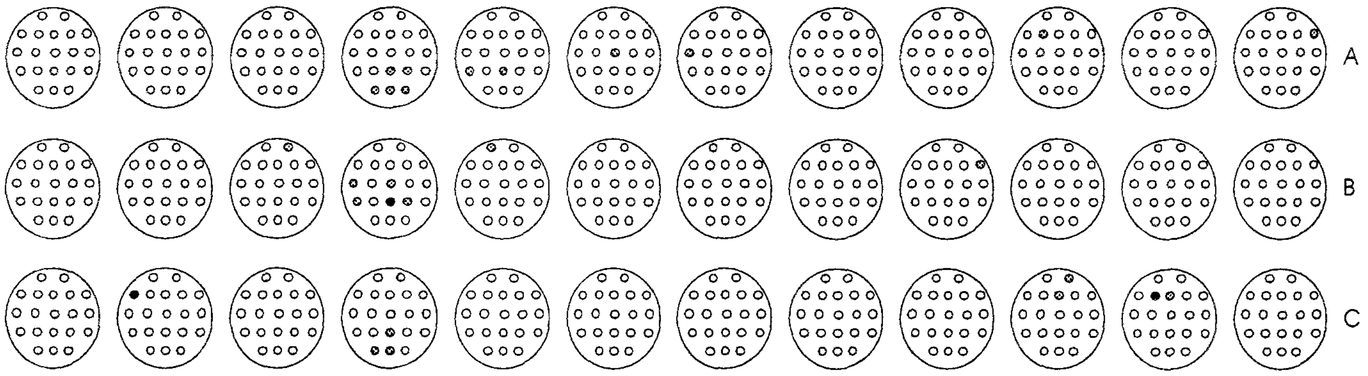

Figure 8. Serial probability maps calculated for each experimental condition: visual warning signal (A), memory set (B) and probe (C) displaying the significance of any differences between VOWELS and TONES in the lower (8-10 Hz) alpha frequency band for each electrode. Each row represents a 3000 msec epoch and each map represents a 250 msec time window. Solid circles p<0.01, dot within circle p<0.05.

msec. This was due to the fact that in that time window, auditory stimulation elicited ERD in the 8-10 Hz frequency band and ERS in the 10-12 Hz frequency band. After the presentation of the probe tone, the frequency bands differed significantly (p<.05) at 750 - 1000 msec. This is explained by the fact that the ERD elicited by the probe was greater (50%) in the 8-10 Hz frequency band than the ERD in the 10-12 Hz frequency band (70%).

4. Differences between the two stimulation types for the two alpha frequency bands.

8-10 frequency band (figure 8). After the presentaion of the visual warning signal, there were no statistically significant differences between the ERD/ERS of the two stimulation groups. After the presentation of the memory set, the stimulation types differed significantly (p<.01) at 500 - 1000 msec and (p<.05) at 1250 - 1500 msec. These differences were due to two facts: tones elicited ERS at 500 msec and the ERS elicited by vowels (150%) at 1250 msec was greater than that for tones (130%). After the presentation of the probe, the stimulation types differed significantly (p<.01) at 250 - 750 msec and (p<.05) at 1250 - 2000 msec. These differences are explained by the frontal ERS being elicited by probe tones but not by probe vowels at 250 msec and by the fact that vowels elicited a longer-lasting ERD (50%) than tones at 1250 - 2000 msec.

10-12 Hz frequency band (figure 9). After the presentation of the visual warning signal, the stimulation groups differed significantly at 2500 - 2750 msec. After the presentation of the memory set, the stimulation types differed significantly (p<.01) at 750 - 1750 msec and at 2500 - 2750 msec. These differences are explained by the

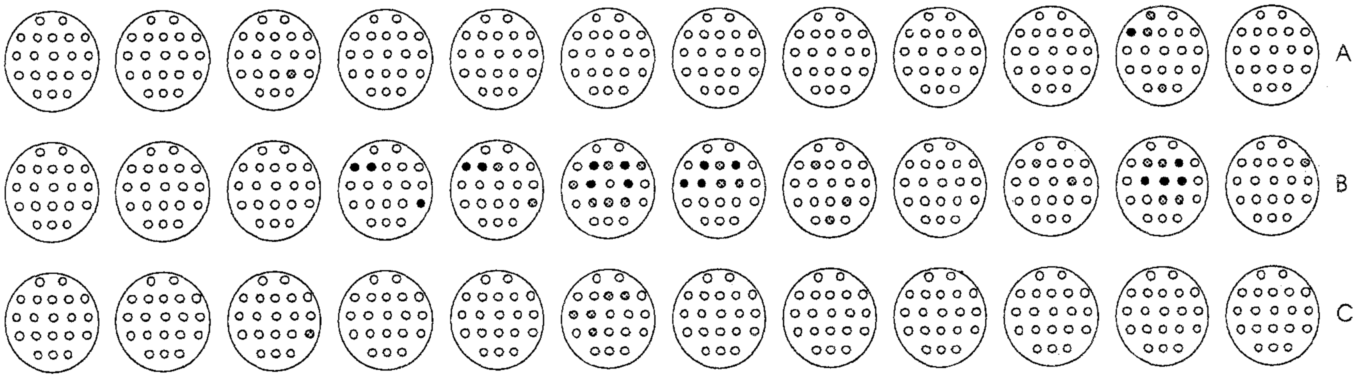

Figure 9. Serial probability maps calculated for each experimental condition: visual warning signal (A), memory set (B) and probe (C) displaying the significance of any differences between VOWELS and TONES in the upper (10-12 Hz) alpha frequency band for each electrode. Each row represents a 3000 msec epoch and each map represents a 250 msec time window. Solid circles $p<0.01$, dot within circle $p<0.05$.

fact that the presentation of vowels elicited greater ERS (150%) than tones (130%). After the presentation of the probe, the stimulation types differed significantly ($p<.05$) at 1250 - 1500 msec. This is due to the fact that probe vowels elicited greater ERD (50%) than probe tones (70%) at 1250 - 1500 msec.

Discussion

The results of this exploratory study suggest that in the auditory stimulus modality, the reactivity of 8-10 Hz and 10-12 Hz frequency bands differ markedly: the ERD of the lower alpha frequency band is longer lasting and topographically more widespread than that of the upper alpha frequency band after the presentation of the visual warning signal as well as after the presentation of the probe. This is in accordance with earlier findings of Pfurtscheller and Klimesch (1992a). During the presentation of the memory set, the ERS was found to be longer lasting and more widespread in the upper than in the lower alpha frequency band. This finding suggests that the upper alpha frequency band reflects stimulus-related processing (Pfurtscheller et al. 1988; Klimesch et al. 1992) also in the auditory stimulus modality. The differences between the lower and upper alpha frequency bands were more prominent for vowels, indicating that the two alpha frequency bands differ in their reactivity to auditory stimulus type. However, some studies indicate that the augmentation of the 10-12 Hz frequency band, observed during and after auditory stimulation, might represent an enhancement of the subject s alpha peak frequency in the ongoing EEG, or represent a separate, higher frequency phenomenon (Makeig 1993).

Why did vowels elicit greater ERD/ERS than tones in both frequency bands? One possibility is that the presentation of vowels (but not tones) activated corresponding phonetic templates, reflected as more marked ERD/ERS. Template matching may also have rendered memory performance easier for vowels than for tones in our experiment. Another explanation could be that there exist multiple cognitive strategies for the processing of vowels (e.g., visualization) which differ from those strategies available for the processing of tones and timbre.

As there were no significant pre-existing differences between the two stimulation groups concerning the studied alpha characteristics, mean IAPF and its amplitude, one can only speculate as to the origin of the significant difference between the two stimulation groups after the presentation of the visual warning signal in the 10-12 Hz frequency band. It should be noted that there were significant differences in the memory performance between the subject/stimulation groups as well as a considerable variability in the memory performance in both groups. These differences could be explained either by differences in stimulus type or by differences between the subject groups. It has been reported that individual alpha frequency at rest is related to memory performance. Good performers exhibit generally higher frequencies than age-matched bad performers, and for good performers this frequency remains at a constant level even if memory-related task demands increase (Klimesch et al. 1993). In accordance with this, in this study, the subjects receiving vowels exhibited a higher IAPF and performed better in the memory task than did the subjects receiving tones. In subsequent studies, it would be interesting to explore whether and how individual memory performance is reflected in ERD/ERS.

For vowels, the presentation of the memory set elicited a topographically more widespread and longer-lasting ERS than for tones, especially in the 10-12 Hz frequency band. For vowels, the presentation of the probe elicited a more widespread and longer- lasting ERD than for tones in the 8-10 Hz frequency band. A careful examination of the power of both frequency bands in the reference interval would clarify whether the desynchronization of the 8-10 Hz frequency band and the synchronization of the 10-12 Hz frequency band are due to differences in the baseline power of the studied frequency bands rather than to differences in reactivity to experimental conditions.

In the 10-12 Hz frequency band, the presentation of the probe elicited a greater ERD for vowels than for tones. The presence of ERS during the presentation of the memory set supports the assumption that the ERD phenomenon does not reflect primary stimulus perception at the auditory cortex. Such an early phase in stimulus processing may not be readily observable in scalp EEG.

To summarize, the results of this exploratory study suggest that ERD is closely related to memory processes and that it reflects the vowel-tone distinction. The ERD/ERS-technique might also provide a valuable tool for future research in the auditory stimulus modality encompassing more complex stimuli such as speech and music.

References

Aranibar, A. and Pfurtscheller, G. On and off effects in the background EEG activity during one-second photic stimulation. Electroenceph. Clin. Neurophysiol., 1978, 44: 307-316.

Beaumont, G. The EEG and task performance: a tutorial review. In: A.W.K. Gaillard and W. Ritter (Eds.), Tutorials in ERP Research: Endogenous Components. North-Holland Publishing Company, 1983: 385-407.

Brust, J. Music and language. Musical alexia and agraphia. Brain. 1980, 103: 367-392.

Crummer, G., Walton, J., Wayman, Hantz, E., Frisina, R. Neural processing of musical timbre by musicians, nonmusicians and musicians possessing absolute pitch. J. Acoust. Soc. Am., 1994, 95: 2720-2727.

Dujardin, K., Derambure, P., Defebre, L., Bourriez, J.L., Jacquesson, J.M. and Guieu, J.D. Evaluation of event-related desynchronization (ERD) during a recognition task: effect of attention. Electroenceph. Clin. Neurophysiol., 1993, 86: 353-356.

Klimesch, W., Pfurtscheller, G. and Mohl, W. ERD mapping and long-term memory: The temporal and topographical pattern of cortical activation. In: G. Pfurtscheller and F.H. Lopez da Silva (Eds.), Functional Brain Imaging. Hans Huber, Toronto, 1988: 131-141.

Klimesch, W., Pfurtscheller, G., Mohl. and Schimke, H. Event-related desynchronization, ERD-mapping and hemispheric differences for words and numbers. Int. J. Psychophysiol., 1990, 8: 297-308.

Klimesch, W., Pfurtscheller, G. and Schimke, H. Pre- and post-stimulus processes in category judgement tasks as measured by event-related desynchronization (ERD). J. Psychophysiol., 1992, 6: 185-203.

Klimesch, W., Schimke, H. and Pfurtscheller, G. Alpha frequency, cognitive load and memory performance. Brain Topography, 1993, 5: 241-251.

Krause, C., Lang, H., Laine, M., Helle, S., Kuusisto, M. and Pörn, B. Event-related desynchronization in the auditory stimulus modality. Brain Topography, 1994, 7: 107-112.

Makeig, S. Auditory event-related dynamics of the EEG spectrum and effects of exposure to noise. Electroenceph. Clin. Neurophysiol., 1993, 86: 283-293.

Petsche, H., Lindner, K., Rappelsberger and Gruber, G. The EEG: an adequate method to concretize brain processes elicited by music. Music Perception. 1988, 6: 133-160.

Petche, H., Rappelsberger, P. and Pockberger, H. Sex differences in the ongoing EEG: probability mapping at rest and during cognitive tasks. In: G. Pfurtscheller and F.H. Lopes da Silva (Eds.), Functional Brain Imaging, Toronto: Hans Huber, 1988: 161-169.

Pfurtscheller, G. Graphical display and statistical evaluation of event-related desynchronization (ERD). Electroenceph. Clin. Neurophysiol., 1977, 43: 757-760.

Pfurtscheller, G. and Aranibar, A. Event-Related cortical desynchronization detected by power measurements of scalp EEG. Electroenceph. Clin. Neurophysiol., 1977, 42: 817-826.

Pfurtscheller, G. and Aranibar, A. Evaluation of event-related desynchronization (ERD) preceding and following voluntary self-paced movement. Electroenceph. Clin. Neurophysiol., 1979, 46: 138-46.

Pfurtscheller, G., Steffan, J. and Maresch, H. ERD mapping and functional topography: Temporal and spatial aspects. In: G. Pfurtscheller and F.H. Lopes da Silva (Eds.), Functional Brain Imaging, Toronto: Hans Huber, 1988: 117-130.

Pfurtscheller, G. Spatiotemporal analysis of alpha frequency components with the ERD technique. Brain Topography, 1989, 2: 3-8.

Pfurtscheller, G. and Klimesch, W. Topographical display and interpretation of event-related desynchronization during a visual-verbal task. Brain Topography, 1990, 3: 85-93.

Pfurtscheller, G. and Klimesch, W. Event-related desynchronization during motor behavior and visual information processing. In: C.H.M. Brunia, G. Mulder and M.N. Verbaten (Eds.), Event-Related Brain Research, Amsterdam: Elsevier, 1991: 58-65.

Pfurtscheller, G. Event-Related Synchronization (ERS): An electrophysiological correlate of cortical areas at rest. Electroenceph. Clin. Neurophysiol., 1992, 83: 62-69.

Pfurtscheller, G. and Klimesch, W. Event-related synchronization and desynchronization of alpha and beta waves in a cognitive task. In: E. Basar, W.J. Freeman, W.-D. Heiss, D. Lehmann, F.H. Lopes da Silva and E.-J Speckmann (Eds.), Brain Dynamics. Boston, Birhauser, 1992a.

Pfurtscheller, G. and Klimesch, W. Functional topography during a visuoverbal judgement task studied with event-related desynchronization mapping. J. Clin. Neurophysiol., 1992b, 9: 120-131.

Pfurtscheller, G. and Neuper, C. Simultaneous EEG 10 Hz desynchronization and 40 Hz synchronization during finger movements. Neuroreport, 1992, 3: 1057-1060.

Schulter, G., Kreuzthaler, A. and Pfurtscheller, G. Ear dominance and laterality of cortical activation identified by event-related desynchronization mapping. Int. J. Psychophysiol., 1990, 8: 283-295.

Sidtis, J. The complex tone test: Implications for the assessment of auditory laterality effects. Neuropsychologia, 1981, 19: 103-112.

Sternberg, S. High-speed scanning in human memory. Science, 1966, 153: 652-654.

Van Winsum, W., Sergeant, J. and Geuze, R. The functional significance of ERD of alpha rhythm in attentional and activating tasks. Electroenceph. Clin. Neurophysiol., 1984, 58: 519-524.