Revista Española de Neuropsicología
Vol. 2, No. 1-2, 77-91 ISSN: 1139-9872

Auditorily Elicited Event-Related Desynchronization (ERD) and Synchronization (ERS) as a Method for Studying Cortical Correlates of Cognitive Processes

Christina M. Krause*
Laboratory of Computational Engineering, Helsinki University of Technology

The present paper reviews recent findings on event-related desynchronization and synchronization (ERD/ERS) elicited by complex auditory stimulation in association with cognitive tasks. The auditorily elicited ERD/ERS responses reflect higher-level cognitive processes such as attention, memory functions and conscious stimulus discrimination. The simultaneously recorded ERD/ERS responses of different EEG frequency bands differ as a function of time and cognitive processes. Dissociations between the neural correlates of the processing of different types of auditory stimuli (e.g., verbal vs non-verbal, aggressive vs depressive etc.) can be assessed by means of the ERD/ERS technique. Narrow frequency band ERD/ERS analysis of the EEG offers a powerful tool for studying cortical activation patterns, and subtle differences between these as a function of various mental, cognitive, memory-related and also emotion-related processes. *Keywords*: EEG - Event-Related Desynchronization - Event-Related Synchronization - Auditory - Cognitive - Memory.

Desincronización (DRE) y Sincronización Relacionada con Potenciales Evocados Auditivos (SER) como Método para Estudiar Correlacciones Corticales de Procesos Cognitivos

Se revisan los resultados de la sincronización y desincronización relacionada con potenciales evocados elicitados por estimulación auditiva compleja asociada con tareas cognitivas. Las respuestas elicitadas auditivamente reflejan un procesamiento cognitivo de alto nivel como atención, funciones de memoria y discriminación conciente de estímulos. Las respuestas DRE/SER grabadas de diferentes bandas de frecuencia EEG se diferencian en función del tiempo y los procesos cognitivos de

---

* The author wishes to thank acknowledge the contributions of Ms. Carina Saarela for her assistance with the graphics. Correspondence to the author should be addressed to the Laboratory of Computational Engineering, PB 9400, 02015 Helsinki University of Technology, Finland. Email: krause@lce.hut.fi (www.lce.hut.fi/~krause). This research was funded by the Academy of Finland (projects 7338 and 42536), by the Cultural Foundation of Southwestern Finland and by the Åbo Akademi Research Foundation. This work has also been funded by the Academy of Finland, Research Centre for Computational Science and Engineering (project 44897, Finnish Centre of Excellence Programme 2000-2005).

desincronización y sincronización. El análisis de frecuencia del EEG ofrece una herramienta poderosa para estudiar los patrones de activación cortical.

The nineties have been called the "Decade of the Brain", making the brain perhaps the only organ that has a decade dedicated to. Numerous novel methods of brain research have flourished in the brain and cognitive sciences, increasing our knowledge of the ways in which the human brain processes information. Experimental studies utilizing both neurophysiological (EEG; electroencephalogram) and neuroimaging (fMRI; functional magnetic resonance imaging, PET; positron emission tomography) techniques in association with cognitive processing have provided an opportunity to approach brain-behavior relationships in a more direct and empirical manner than ever before (Klimesch, Pfurtscheller, Mohl & Schimke, 1990; Canli, Desmond, Zhao, Glover & Gabrieli, 1998; Fernández, Harmony, Silva, Galán, Diaz-Comas, Bosch, Rodriguez, Fernández-Bouzas, Yáñez, Otero & Marosi, 1998). Although being one of the oldest psychophysiological investigation methods, the EEG is characterized by a superb time resolution which makes it highly effective especially for studying the temporal arrangement of brain processes.

Research on the electroencephalogram (EEG) can be traced back to 1875, to the work of Richard Caton. In 1929, Hans Berger discovered in the ongoing EEG the so-called alpha rhythm in man and was able to demonstrate that some of the activity originated in the brain itself and was not due to the activity of the scalp musculature (Berger, 1929). The rhythmic, ongoing EEG activity caused by the minor currents of the neural elements of the brain can be recorded simultaneously from multiple sites on the scalp or from the surface of the brain by means of the EEG. While the EEG is one of the most widely used neuro- and psychophysiological measurement techniques, the nature of the generators in the brain responsible for the EEG are still largely a matter of debate (Steriade, Gloor, Llinas, Lopes da Silva & Mesulam, 1990). The EEG consists of several simultaneous oscillations which have traditionally, based on visual examination, been subdivided in frequency bands such as theta (4-8 Hz), alpha (8-12 Hz), beta (about 14-30 Hz) and gamma (around 40 Hz). It has been proposed that different neural generators would be involved in the propagation of different EEG oscillations (Fernández et al., 1998). For example, hippocampal neural activity seems to be reflected as oscillations within the theta frequency band (~4-8 Hz) (Burgess & Gruzelier,1997; Klimesch, 1996a; Klimesch, 1999) while the alpha rhythm (~8-12 Hz) is generated mainly by cortico-cortical and thalamocortical neural networks

(Steriade et al., 1990; Klimesch, Schimke & Schwaiger, 1994; Klimesch, 1997). During stimulation, the simultaneously recorded responses of different EEG frequency bands differ from each other (Klimesch, Doppelmayr, Schimke & Ripper, 1997; Pfurtscheller & Klimesch, 1992b; Steriade et al., 1990), and reflect different cognitive and/or mental processes or states (Boiten, Sergeant & Geuze, 1992; Klimesch et al., 1994; Klimesch, 1996a; Klimesch, Russegger, Doppelmayr & Pachinger, 1998a; Dumont, Macchi, Carrier, Lafrance & H,bert, 1999). E.g., working memory processes seem to be reflected as oscillations within the EEG theta frequencies (~4-8 Hz) (Klimesch et al., 1997; Klimesch, 1999), 8-10 Hz alpha activity seems to be modulated as a function of attentional demands (Klimesch, Pfurtscheller & Schimke, 1992) and oscillations around 10-12 Hz are modulated mainly by stimulus-related aspects and/or semantic memory processes (Klimesch et al., 1994; Klimesch, 1996b; Klimesch, Doppelmayr, Russegger, Pachinger & Schwaiger, 1998b).

Event-related desynchronization (ERD) and synchronization (ERS)

Event-Related Desynchronization (ERD) and Synchronization (ERS) - analysis of the EEG is one way to assess the stimulus-related responses of different EEG frequencies (Aranibar & Pfurtscheller, 1978; Pfurtscheller & Aranibar, 1977). ERD is defined as the phasic relative amplitude decrease whereas ERS denotes the phasic relative increase in amplitude of a defined frequency band occurring in relation to an event (Pfurtscheller, 1992). Figure 1. displays digitally bandpass filtered 8-10 Hz EEG data and temporal changes in amplitude, i.e., synchronization (black arrow; increase in amplitude) and desynchronization (white arrow; decrease in amplitude). Electrode locations are depicted on the Y-axis whereas the X-axis stands for time. The time between the thick vertical lines is 1000 msec. The broken vertical lines denote stimulus presentation (STIM). Synchronization is indicated by a black arrow and desynchronization by a white arrow.

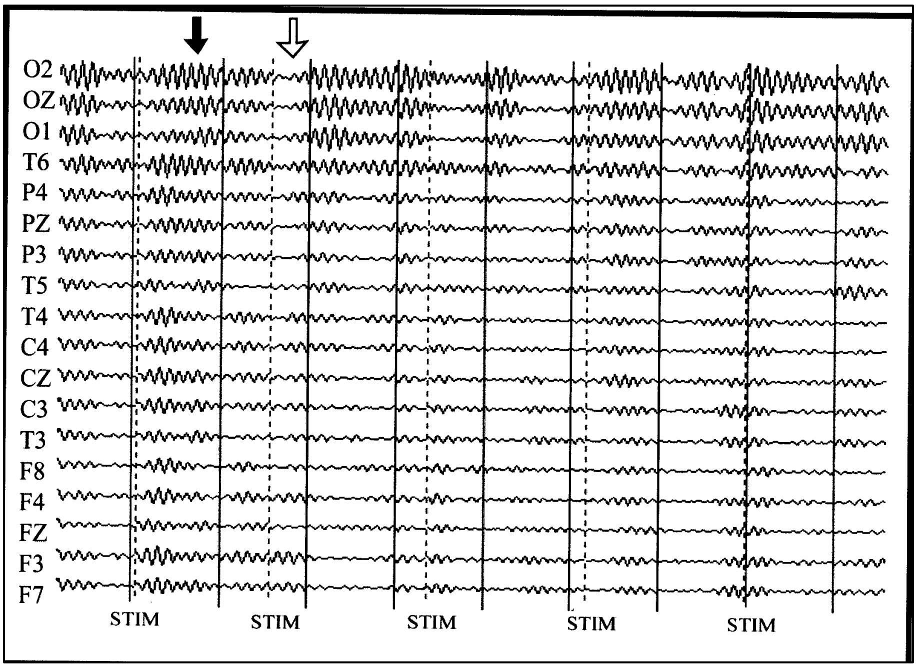

Figure 1. A 10 second example of digitally bandpass filtered 8-10 Hz EEG data.

The quantification of ERD/ERS is based the comparison of two different experimental conditions. ERD/ERS is then defined as the relative difference in EEG power between the two conditions as a function of time (Pfurtscheller, Steffan & Maresch, 1988). ERD/ERS is thus a "within-subject" measure of cortical activation and is expressed as a percentage. ERD mapping is the topographical display of event-related desynchronization and synchronization which can be used to investigate cortical activation patterns in time and space (Pfurtscheller 1977; Pfurtscheller et al. 1988; Pfurtscheller & Klimesch 1990). ERD mapping is a brain imaging technique which allows portrayal of regional brain activity with a relatively high temporal resolution. The example in Figure 2. shows ERD/ERS maps during an auditory memory task. Typically, encoding of auditory material elicits ERS (upper row) whereas retrieval of auditory material evokes ERD (lower row).

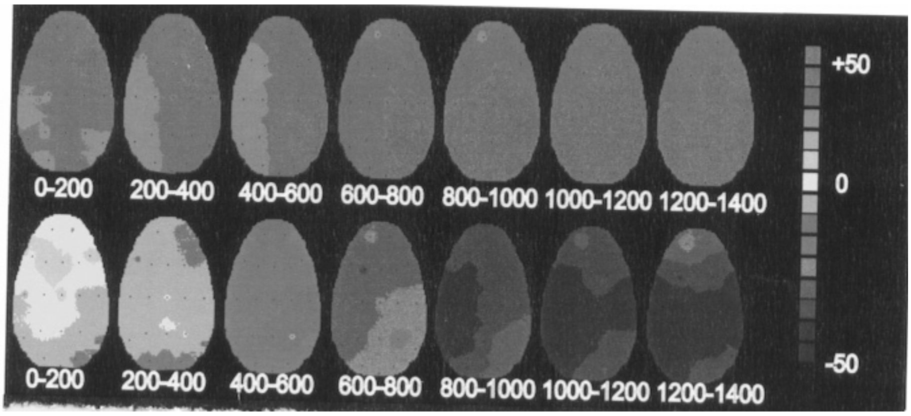

Figure 2. ERD/ERS maps (nose upward) displaying changes in 8-10 Hz power.

ERD of the alpha frequencies has been observed during visual stimulation (Aranibar and Pfurtscheller, 1978; Pfurtscheller & Aranibar, 1977; Pfurtscheller et al., 1988; Pfurtscheller, Neuper & Mohl, 1994), during simple auditory stimulation (Pfurtscheller & Aranibar, 1977; Schulter, Kreutzhaler, & Pfurtscheller, 1990), during voluntary movement tasks (Mohl & Pfurtscheller, 1991; Pfurtscheller & Aranibar, 1979; Pfurtscheller & Berghold, 1989; Pfurtscheller & Neuper, 1992) and also during cognitive and attentional tasks (Boiten et al., 1992; Dujardin, Derambure, Defebre, Bourriez, Jaquesson & Guieu, 1993; Dujardin, Bourriez & Guieu, 1994; Klimesch, Pfurtscheller & Mohl, 1988; Klimesch et al., 1990; 1992; Klimesch, Schimke & Pfurtscheller, 1993; Pfurtscheller and Klimesch, 1990; 1992a; 1992b; Pfurtscheller et al., 1994; Van Winsum, Sergeant & Geuze, 1984). Auditorily elicited ERD/ERS in association with cognitive processes has mainly been studied by Krause and co-workers (Krause, Lang, Laine, Helle, Kuusisto & Pörn, 1994; Krause, Lang, Laine, Kuusisto & Pörn, 1995; Krause, Lang, Laine & Pörn,1996; Krause, Pörn, Lang & Laine, 1997; Krause, Korpilahti, Pörn, Jäntti & Lang, 1998; Krause, Åström, Karrasch, Laine & Sillanmäki, 1999a; Krause, Pörn, Lang & Laine, 1999b; Karrasch, Krause, Laine & Lang, 1998; Lähteenmäki, Krause, Salmi & Lang, 1999).

By means of ERD/ERS, investigators have been able to detect characteristic changes in brain electric oscillatory activity during various cognitive and attentional tasks in the visual, motor, and recently also in the auditory stimulus modality. As the EEG, also the ERD/ERS is characterized by a very good time resolution and additionally by a very high reliability (Burgess & Gruzelier, 1996).

Auditorily elicited ERD/ERS

Auditorily elicited ERD/ERS has mainly been studied by Krause and co-workers (Karrasch et al., 1998; Krause et al., 1994; 1995; 1996; 1997; 1998; 1999a; 1999b; Krause, 1999; Lähteenmäki et al., 1999). The studies conducted by Krause and co-workers have shown that the ERD/ERS elicited by complex auditory stimulation is associated with cognitive processes such as memory functions and conscious stimulus discrimination rather than with primary auditory processing per se. Krause and co-workers have demonstrated that the auditorily elicited ERD/ERS is very suitable for studying cortical correlates of "higher-level" auditory information processing.

In their first report, Krause et al. (1994) reported that ERD was elicited in the lower (8-10 Hz) and the upper (10-12 Hz) alpha frequency bands during and after the presentation of short auditorily presented phrases which the subjects were instructed to memorize. In that initial study, it was proposed that the ERD observed in that study most probably reflected attentional processes or memory-related functions rather than auditory processing per se.

In 1996, Krause et al. (1996) examined auditorily elicited ERD/ERS in ten normal subjects using the Sternberg (1966) memory-search paradigm. The memory set consisted of four synthesized auditory vowels and the probe consisted of one auditory vowel. The subjects had to decide whether the fifth vowel was earlier presented in the memory set and then to indicate their answer by pressing a button on a response pad. The presentation of the memory set (auditory encoding) elicited a significant ERS in both alpha frequency bands. By contrast, the presentation of the probe (auditory retrieval) elicited a significant ERD in both alpha frequency bands. Auditorily elicited ERD/ERS of the 8-10 Hz and 10-12 Hz alpha frequency bands has also been studied during an auditory memory task with synthesized instrument sounds, resembling those of different instruments, as stimuli (Krause et al., 1995). In that study also, the presentation of the memory set elicited ERS in both alpha frequency bands whereas the presentation of the probe elicited ERD in both alpha frequency bands. When the ERD/ERS responses for vowels and tones were compared (Krause et al., 1995) differences between the ERD/ERS of the 8-10 Hz and 10-12 Hz frequency bands were found for vowels only. This finding verified that the two alpha frequency bands differ in their reactivity to auditory stimulus type. The presentation of vowels might have activated corresponding phonetic templates, not available for tones and timbre, which in turn might have made it possible to use template matching or to use multiple cognitive strategies for the encoding/retrieval of vowels.

Auditorily elicited relative alpha desynchronization and synchronization has been studied during speech perception. Krause et al. (1997) presented to their subjects a five-minute spoken text passage presented both forward and backward. While listening to the text forward, subjects were instructed to memorize the contents of the text. A significant effect for the stimulus type was observed so that listening to and memorizing the text elicited ERD whereas listening to the text backward elicited ERS. The significant interaction between frequency band and stimulus type indicated that the 8-10 Hz and 10-12 Hz frequency bands differed such that the 10-12 Hz frequency band exhibited reactivity to the presence of linguistic content while the 8-10 Hz band showed an unspecific response. The results from this study indicate that the auditorily elicited responses of the upper alpha frequency band are language (or memory)-related, whereas those of the lower are not.

Auditorily elicited ERD/ERS has also been examined during an auditory lexical decision task (Karrasch et al., 1998). In that study, the stimuli were auditory presented Finnish words and pseudowords presented sequentially in pairs. The subjects were instructed to answer whether the two stimuli belonged to the same lexical category. The main finding of this study was that regardless of lexicality, the presentation of the first stimulus (encoding) elicited a significant ERS. The presentation of the second stimulus (comparison) elicited ERD which, however, varied in magnitude and latency as a function of stimulus type and previous stimulus type. Karrasch et al. (1998) suggested that the ERD observed in their study did not reflect primary auditory stimulus processing. The ERD/ERS observed in their study most probably reflected subtle differences between lexical-semantic and phonological memory functions.

In 1999, Krause et al. (Krause et al., 1999a) examined cortical correlates of semantic memory processes in the auditory stimulus modality by means of the ERD/ERS technique while the subjects were performing an auditory semantic matching task. The stimuli were abstract and concrete nouns which were presented sequentially in pairs. The task was to decide whether the two nouns belonged to the same semantic category or not. Krause et al. (1999a) reported that the presentation of the first stimulus (encoding) elicited alpha ERS whereas the presentation of the second stimulus (semantic matching) elicited alpha ERD. Abstract nouns presented as the second stimulus elicited alpha ERD which was most prominent in the lower alpha frequency band whereas the presentation of a concrete noun as the first stimulus elicited ERS, most prominently in the upper alpha frequency band. Their findings demonstrate that the auditorily elicited ERD/ERS can reveal subtle differences in auditory information processing. Semantic memory processes (encoding and comparison) seem to be reflected as varying responses in the two alpha frequency bands.

Auditorily elicited relative alpha desynchronization and synchronization has also been studied during music perception by Krause et al. (Krause et al., 1999b). The subjects listened to two different five-minute musical excerpts, one popular and the other classical, presented both forward and backward. In this study, the ERD/ERS responses of the 8-10 Hz and 10-12 Hz were examined with regard to the "musicality" of the stimulation (forward vs. backward) as well as to its musical genre (popular vs. classical). The results from this study revealed that the ERD/ERS responses of the 8-10 Hz and 10-12 Hz frequency bands were dissimilar, dynamic, and dependent on stimulation type as a function of time. The differences in the ERD/ERS responses between the different musical genres were most prominent in the 10-12 Hz frequency band. The lower alpha responses were modulated as a function of time.

In 1999, Lähteenmäki et al. (Lähteenmäki et al., 1999) examined the long term effects of childhood cancer treatment on adolescent cancer survivors by means of ERD/ERS while the subjects performed an auditory memory task (Krause et al., 1996). In that study (Lähteenmäki et al., 1999) it was observed that childhood cancer treatment had long-lasting effects on the ERD/ERS reponses, especially in the 8-10 Hz frequency band, being most pronounced in leukemia survivors. Lähteenmäki et al. (1999) concluded that such changes in the responses of this alpha frequency band might shed some light on the often-reported attentional problems after cancer treatment.

The term "affective neuroscience" refers to the study of neural mechanisms associated with human emotions. Recently Krause, Åström, Karrasch, Sillanmäki & Alanko (1999c) examined the ERD/ERS responses of the 4-6, 6-8, 8-10 and 10-12 Hz frequency bands while the subjects were performing an auditory memory task with three types of emotion-related stimuli: aggressive, depressive and neutral. The results demonstrated that in the theta frequency range (4-6 and 6-8 Hz), the responses elicited by different emotion-related verbs differed as a function of time and cognitive task (encoding vs. retrieval). In the alpha frequencies (8-10 and 10-12 Hz), the retrieval of aggressive and depressive verbs elicited ERD, especially over the right hemisphere. Thus, dissociations between the neural correlates of the encoding and retrieval of different types of emotion-related auditory stimuli were observed in brain electric oscillatory activity and the ERD/ERS method was appropriate for assessing these. The ERD/ERS analysis of the EEG seems to offer a powerful tool for studying cortical activation patterns also during emotion-related processes.

Krause, Sillanmäki, Koivisto, Häggqvist, Saarela, Revonsuo, Laine and Hämäläinen (2000) have lately examined the effects of electromagnetic fields (EMF) emitted by cellular phones on the ERD/ERS of the 4-6 Hz, 6-8 Hz, 8-10 Hz and 10-12 Hz EEG frequency bands while subjects were performing an auditory working memory task. The exposure to EMF significantly increased EEG power but only in the 8-10 Hz frequency band. Nonetheless, the presence of EMF altered the ERD/ERS responses in all studied frequency bands as a function of time and cognitive task (memory encoding vs. retrieval). It was observed that the exposure to EMF seems not to alter the EEG per se but modifies the brain responses significantly during information processing. The exposure to EMF might thus have a significant influence on neural oscillatory systems, especially when information is being processed. Such findings are encouraging while illuminating the biological (neural) grounds for often reported behavioral alterations (in, e.g., reaction times) as a result of exposure to EMF (Koivisto, Revonsuo, Krause, Haarala, Sillanmäki, Laine & Hämäläinen, 2000).

Conclusions

Human cognition represents the highest and most creative level of information processing. It should be noted that very little is still known about the exact mechanisms how information is stored and accessed in the human brain (Klimesch, 1997). It has been proposed that brain electric oscillations would be of fundamental importance for mediating these "higher-level" processes (Jensen, Idiart & Lisman, 1996a; Jensen & Lisman, 1996b; 1996c; Klimesch, Doppelmayr, Schwaiger, Auinger & Winkler, 1999; Klimesch, 1994). A review of the investigations in which the ERD/ERS technique has been used to study auditory information processing reveals that the auditorily elicited ERD/ERS reflect attentional and cognitive processes rather than auditory stimulus perception per se. The auditorily evoked ERD/ERS responses of several EEG frequency bands differ systematically from one another as a function of cognitive task. Additionally, the auditorily elicited ERD/ERS responses vary as a function of task demands such as encoding vs. retrieval and stimulus type.

Time and timing are the very essence of auditory information processing. The estimation and understanding of time intervals and/or duration are very essential capacities, e.g., when acquiring language. The ERD/ERS technique allows one to study the modulation of various EEG background rhythms in association with auditory stimulation, as a function of time. By means of this technique, it is possible to examine various aspects of the temporal integration of auditory information far beyond behavioural investigation methods.

At best, with the funding of the Academy of Finland (Christina M. Krause, projects 7338 and 42536), at the Centre for Cognitive Neuroscience, at the University of Turku and at the Laboratory od Computational Engineering at the Helsinki University of Technology, data is being gathered from several experiments focusing on auditory memory processes. Because the ERD/ERS technique seems adequate to reveal subtle dissimilarities in the cortical correlates of different cognitive processes, it seems plausible to speculate that the ERD/ERS technique can also reveal subtle alterations in these, in some conditions of "altered state of mind". Clinical studies with the auditorily elicited ERD/ERS have recently begun in patients suffering from Parkinsonïs disease, Alzheimer´s disease, Aspergers syndrome, schizophrenia, major depression and sleep disorders.

To summarize, the simultaneous ERD/ERD analysis of several narrow frequency bands gives an opportunity to investigate the cortical complexity underlying human information processing capacities not only in association with various cognitive processes but also with emotion-related processes. In future studies, the findings presented in this paper might be of potential importance when utilizing similar, complex cognitive experimental paradigms on some clinical populations suffering from, e.g., biologically determined irregular memory processes (as in Alzheimer´s disease) and/or processing of emotions (as in depression).

References

Aranibar, A., & Pfurtscheller, G. (1978). On and off effects in the background EEG activity during one-second photic stimulation. *Electroencephalography and Clinical Neurophysiology, 44,* 307-316.

Berger, H. (1929). Ueber das elektroenkephalogramm das menchen. *Archiv fuer Psychiatrie, 87,* 527-570.

Boiten, F., Sergeant, J., & Geuze, R. (1992). Event-related desynchronization: the effects of energetic and computational demands. *Electroencephalography Clinical Neurophysiology, 82*, 302-209.

Burgess, A.P., & Gruzelier, J.H.. (1996) The reliability of event- related desynchronization: a generalisability study analysis. International *Journal of Psychophysiology, 23*, 163-169.

Burgess, A.P., & Gruzelier, J.H. (1997). Short duration synchronization of human theta rhythm during recognition memory. *NeuroReport, 8,* 1039-1042.

Canli, T., Desmond, J.E., Zhao, Z., Glover, G., & Gabrieli, D.E. (1998). Hemispheric asymmetry for emotional stimuli detected with fMRI. *NeuroReport, 9*, 3233-3239.

Dujardin, K., Bourriez, J.L., & Guieu, J.D. (1994). Event-related desynchronization (ERD) patterns during verbal memory tasks. *International Journal of Psychophysiology, 16*, 17-27.

Dujardin, K., Derambure, P., Defebre, L., Bourriez, J.L., Jaquesson, J.M., & Guieu, J.D. (1993). Evaluation of event-related desynchcronization (ERD) during are cognition task: effect of attention. *Electroencephalography and Clinical Neurophysiology, 86*, 353-356.

Dumont ,M., Macchi, M.M., Carrier, J., Lafrance, C., & Hébert, M. (1999) Time course of narrow frequency bands in the waking EEG during sleep deprivation. *NeuroReport, 10*, 403-407

Fernández, T., Harmony, T., Silva, J., Gal n, L., Diaz-Comas, L., Bosch, J., Rodriguez, M., Fernández-Bouzas, A., Yáñez, G., Otero, G., & Marosi, E. (1998) Relationship of specific EEG frequencies at specific brain areas with performance. *NeuroReport, 9,* 3681-3687.

Jensen, O., Idiart, M.A.P., & Lisman, J.E. (1996a) Physiologically realistic formation of autoassociative memory in networks with theta/gamma oscillations: role of fast NMDA channels. *Learning and Memory, 3,* 243-256.

Jensen, O., & Lisman, J.E. (1996b) Novel lists of 7+/- 2 known items can be reliably stored in an oscillatory short-term memory network: interaction with long-term memory. *Learning and Memory, 3,* 257-263.

Jensen, O., & Lisman, J.E. (1996c) Theta/gamma networks with slow NMDA channels learn sequences and encode episodic memory: role of NMDA channels in recall. *Learning and Memory, 3*, 264-278.

Karrasch, M., Krause, C.M., Laine, M., & Lang, A.H. (1998). Event-related desynchronization during an auditory lexical matching task. *Electroencephalography and Clinical Neurophysiology*, *107*, 112-121.

Klimesch, W. (1996a) Memory processes described as brain oscillations in the EEG-alpha and theta bands. PSYCOLOQUY, 6, memory-brain.1. klimesch.

Klimesch, W. (1996b) Memory processes, brain oscillations and EEG synchronization. *International Journal of Psychophysiology*, *24*, 61-100.

Klimesch, W. (1997) EEG-alpha rhythms and memory processes.International *Journal of Psychophysiology*, *26*, 319-340.

Klimesch, W. (1999) Event-related band power changes and memory performance. In G. Pfurtscheller & F.H Lopez da Silva (Eds.), *Event-Related Desynchronization - Handbook of Electroencephalography and Clinical Neurophysiology* (pp. 161-178). Amsterdam: Elsevier Science.

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., & Schwaiger, J. (1998b) Induced alpha band power changes in the human EEG and attention. *Neuroscience Letters, 244,* 73-76.

Klimesch, W., Doppelmayr, M., Schimke, H., & Ripper, B. (1997) Theta synchronization and alpha desynchronization in a memory task. *Psychophysiology, 34*, 169-176.

Klimesch, W., Doppelmayr, M., Schwaiger, J., Auinger, P., & Winkler, Th. (1999) "Paradoxical" alpha synchronization in a memory task. *Cognitive Brain Research*, *7*, 493-501.

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

Klimesch, W., Pfurtscheller, G., Mohl, W., & Schimke, H. (1990). Event-related desynchronization, ERD-mapping and hemispheric differences for words and numbers. *International Journal of Psychophysiology, 8*, 297-308.

Klimesch, W., Pfurtscheller, G., & Schimke, H. (1992). Pre- and post-stimulus processes in category judgement tasks as measured by event-related desynchronization. *Journal of Psychophysiology*, *6*, 185-203.

Klimesch, W., Russegger, H., Doppelmayr, M., & Pachinger, T.(1998a) Induced and evoked band power changes in an oddball task. *Electroencephalography and Clinical Neurophysiology, 108*, 123-130.

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

Klimesch, W., Schimke, H., & Schweiger, I. (1994). Episodic and semantic memory: an analysis in the EEG theta and alpha band. *Electroencephalography and Clinical Neurophysiology, 91,* 428-441.

Krause, C.M. (1999) Event-related EEG changes during auditory processing. In G. Pfurtscheller & F.H Lopez da Silva (Eds.), *Event-Related Desynchronization - Handbook of Electroencephalography and Clinical Neurophysiology* (pp. 195-201). Amsterdam: Elsevier Science.

Krause, C.M., Lang, A.H., Laine, M., Helle, S., Kuusisto, M., & Pörn, B. (1994). Event-related desynchronization evoked by auditory stimuli. *Brain Topography, 7,* 107-112.

Krause, C.M., Lang, A.H., Laine, M., Kuusisto, M., & Pörn, B. (1995). Cortical processing of vowels and tones as measured by event-related desynchronization. *Brain Topography, 8*, 47-58.

Krause, C.M., Lang, A.H., Laine, M., & Pörn, B. (1996). Event-related EEG desynchronization and synchronization during an auditory memory task. *Electroencephalography and Clinical Neurophysiology, 98*, 319-326.

Krause, C.M., Korpilahti, P., Pörn, B., Jäntti, J., & Lang A.H. (1998) Automatic auditory word perception as measued by 40 Hz EEG responses. *Electroencephalography and Clinical Neurophysiology, 107*, 84-87.

Krause, C.M., Pörn, B., Lang, A.H., & Laine, M. (1997). Relative alpha desynchronization and synchronization during speech perception. *Cognitive Brain Research, 5*, 295-299.

Krause, C.M., Pörn, B., Lang, A.H., & Laine, M. (1999b) Relative Alpha Desynchronization and Synchronization During Perception of Music. *Scandinavian Journal of Psychology, 40*, 209-215.

Krause, C.M., Sillanmäki, L., Koivisto, M., Häggqvist, A.,Saarela, C., Revonsuo, A., Laine, M., & Hämäläinen, H. (2000) Effects of electromagnetic field emitted by cellular phones on the EEG during a memory task. *NeuroReport 11,* 761-764.

Krause, C.M., Åström, T., Karrasch, M., Laine, M., & Sillanmäki, L. (1999a) Cortical activation related to auditory semantic matching of concrete vs.abstract words. *Clinical Neurophysiology, 110*, 1371-1377.

Krause, C.M., Åström, T., Karrasch, M., Sillanmäki, L., & Alanko, K. (1999c) Event-related EEG responses during an auditory memory task with emotion-related stimuli. Poster. Second International Tsukuba Conference on Memory, December 18th -21st 1999c, Tsukuba, Japan.

Koivisto, M., Revonsuo, A., Krause, C.M., Haarala, C., Sillanmäki, L., Laine, M.., & Hämäläinen, H. (2000) Effects of 902 MHz electromagnetic field emitted by cellular phones on response times in humans. *NeuroReport, 11*, 413-415.

Lähteenmäki, P., Krause, C.M., Salmi, T.T., & Lang, A.H. (1999) Event-related synchronization/desynchronization as a psychophysiological correlate of impaired attention and memory function after the treatment of childhood cancer. *Clinical Neurophysiology, 110*, 1-10.

Mohl, W., & Pfurtscheller, G. (1991). The role of the right parietal region in a movement time estimation task. *NeuroReport*, *2*, 309-312.

Pfurtscheller, G. (1977). Graphical display and statistical evaluation of event-related desynchronization. Electroencephalography and Clinical *Neurophysiology, 43*, 757-760.

Pfurtscheller, G. (1992). Event-related synchronization (ERS): an electrophysiological correlate of cortical areas at rest. *Electroencephalography and Clinical Neurophysiology, 83*, 62-69.

Pfurtscheller, G., & Aranibar, A. (1977). Event-related cortical desynchronization detected by power measurements of scalp EEG. *Electroencephalography and Clinical Neurophysiology, 42*, 817-826.

Pfurtscheller, G., & Aranibar, A. (1979). Evaluation of event- related desynchronization (ERD) preceding and following voluntary self-paced movement. *Electroencephalography and Clinical Neurophysiology, 46*, 138-146.

Pfurtscheller, G., & Berghold, A. (1989). Patterns of cortical activation during planning of voluntary movement. *Electroencephalography and Clinical Neurophysiology, 72,* 250-258.

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

Pfurtscheller, G., & Klimesch, W. (1992a). 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 & E.-J. Speckmann (Eds.), *Brain dynamics* (pp. 117-128), Boston: Birkhauser.

Pfurtscheller, G., & Klimesch, W. (1992b). Functional topography during a visuoverbal judgement task studied with event-related desynchronization mapping. *Journal of Clinical Neurophysiology, 9*, 120-131.

Pfurtscheller, G., & Neuper, C. (1992). Simultaneous EEG 10 Hz desynchronization and 40 Hz synchronization during finger movements. *NeuroReport, 3*, 1057-1060.

Pfurtscheller, G., Neuper, C., & Mohl, W. (1994). Event-related desynchronization (ERD) during visual processing. International *Journal of Psychophysiology*, *16*, 147-153.

Pfurtscheller, G., Steffan, J., & Maresch, H. (1988). ERD mapping and functional topography: Temporal and spatial aspects. In G. Pfurtscheller & F. H. Lopes da Silva (Eds.), *Functional brain imaging* (pp. 117-130), Stuttgart: Hans Huber.

Schulter, G., Kreutzhaler, A., & Pfurtscheller, G. (1990). Ear dominance and laterality of cortical activation identified by event-related desynchronization. *International Journal of Psychophysiology*, *8*, 283-295.

Steriade, M., Gloor, P., Llinas, R.R., Lopes da Silva, F.H., & Mesulam, M.-M. (1990). Basic mechanisms of cerebral rhythmic activities. *Electroencephalography and Clinical Neurophysiology*, *76*, 481-508.

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

Van Winsum, W., Sergeant, J., & Geuze, R. (1984). The functional significance of ERD of alpha rhythm in attentional and activating tasks. *Electroencephalography and Clinical Neurophysiology*, *58*, 519-524.

Received February 07, 2000
Revision received March 20, 2000
Accepted April 01, 2000