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Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task

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Abstract.

Purpose: To examine the effects of electromagnetic fields (EMF) emitted by cellular phones on the event-related desynchronization/synchronization (ERD/ERS) responses of the 4–6, 6–8, 8–10 and 10–12 Hz EEG frequency bands during cognitive processing.

Materials and methods: Twenty-four subjects performed a visual sequential letter task (*n*-back task) with three different working memory load conditions: zero, one and two items. All subjects performed the memory task both with and without exposure to a digital 902 MHz EMF in counterbalanced order.

Results: The presence of EMF altered the ERD/ERS responses in the 6–8 and 8–10 Hz frequency bands but only when examined as a function of memory load and depending also on whether the presented stimulus was a target or not.

Conclusions: The results suggest that the exposure to EMF modulates the responses of EEG oscillatory activity ~8 Hz specifically during cognitive processes.

1. Introduction

Cellular mobile phones (GSM, Global System for Mobile Communication) emit high-frequency electromagnetic fields (EMF). The close proximity of a mobile phone to the user's head leads to the absorption of EMF energy by the head and brain (Schönborn *et al.* 1998). The possible effects of such fields on the human body and brain have recently been broadly discussed. With regard to the effects of EMF on the EEG, some studies have reported that exposure to EMF ~900 MHz has effects on the EEG (Mann and Röschke 1996, Eulitz *et al.* 1998, Freude *et al.* 1998, Krause *et al.* 2000) whereas not all studies have demonstrated such effects (Röschke and Mann 1997, Wagner *et al.* 1998). The differences in experi-

mental conditions, exposure times to EMF and EEG quantification methods make it very difficult to draw any general conclusions from these few studies.

EEG frequencies are traditionally subdivided in frequency bands such as θ (4–8 Hz), α (8–12 Hz), β (~14–30 Hz) and γ (30–80 Hz). The simultaneously recorded responses of different EEG frequency bands differ from each other (Steriade *et al.* 1990, Pfurtscheller and Neuper 1992, Klimesch *et al.* 1997) and reflect different cognitive and/or mental processes or states (Boiten *et al.* 1992, Klimesch *et al.* 1994, Klimesch 1996, Klimesch *et al.* 1998a, b, Dumont *et al.* 1999). For example, with increasing task demands, θ power tends to increase (i.e. becomes synchronized) as α power decreases (i.e. becomes desynchronized) (Klimesch 1999). It has been proposed that different neural generators would be involved in the propagation of different EEG frequencies (Fernández *et al.* 1998). For example, hippocampal neural activity is reflected within the θ frequency band (~4–8 Hz) (Burgess and Gruzelier 1997) while the α rhythm (~8–12 Hz) is generated mainly by corticocortical and thalamocortical neural networks (Steriade *et al.* 1990, Klimesch *et al.* 1994, Klimesch 1997).

The responses of different EEG frequencies have been associated with different mental processes. Episodic memory processes seem to be reflected as oscillations in the EEG θ frequencies (~4–8 Hz) (Klimesch 1996). In contrast, 8–10 Hz α activity seems to be modulated by attentional demands (Klimesch *et al.* 1992) whereas 10–12 Hz α activity is modulated by semantic memory processes (Klimesch *et al.* 1994, Klimesch 1999).

One way to assess the stimulus-related responses of different EEG frequency bands is the so-called event-related desynchronization (ERD) and synchronization (ERS)—analysis of the EEG (Pfurtscheller 1977, Pfurtscheller and Aranibar 1977, Aranibar and Pfurtscheller 1978). ERD is defined as the phasic relative amplitude decrease whereas ERS denotes the phasic relative increase in amplitude of

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a defined frequency band occurring in relation to an event (Pfurtscheller 1992).

Recently, Krause *et al.* (2000) reported that exposure to EMF significantly altered the ERD/ERS responses in the 4–12 Hz frequency band range during an auditory memory task, especially during memory retrieval. No such effects were observed during memory encoding.

The aim of the present study was to assess the possible effects of EMF exposure on human brain electric oscillatory activity during a visual working memory task (Braver *et al.* 1997). Our subjects performed a visual sequential letter task (*n*-back task) with three different working memory load conditions: zero, one and two items. This experimental paradigm allowed us to examine the effects of the following factors on brain electric oscillatory activity: TIME (1500 ms), EMF (off, on), STIMULUS (non-target, target), MEMORY LOAD (zero, one, two) and HEMISPHERE (left, right). Also analysed was the so-called event-related desynchronization (ERD) and synchronization (ERS) of the 4–6, 6–8, 8–10 and 10–12 Hz narrow EEG frequency bands. The choice of this intrasubject EEG measure (ERD/ERS) was motivated by the high reliability of the method (Burgess and Gruzeliier 1996). Additionally, recent EEG studies strongly suggest that narrow band EEG analyses are more informative than broad band EEG analyses (Doppelmayr *et al.* 1998, Dumont *et al.* 1999, Krause *et al.* 2000).

2. Materials and methods

2.1. Subjects

Twenty-four healthy, right-handed adult volunteers participated in the experiment. Half of the subjects were males and half were females ranging in age from 20 to 30 years (mean = 23.3 years, SD = 2.6). The handedness of the subjects was verified with an unpublished Finnish version of the Boston V.A. Handedness Questionnaire comprising 12 questions about the hand and foot one uses in different tasks such as handwriting, kicking a ball and lighting a match. Subjects were considered as right-handed only if they used the right limb in 10 or more situations. None of the subjects reported any hearing defects, neurological disorders, nor were on medication.

2.2. Cognitive task

The subjects performed a visual sequential letter task (a so-called *n*-back task). Subjects observed stimuli on a visual display and responded using a

hand-held response pad. In the 0-back condition, subjects responded to a single prespecified target letter ('X'). In the 1-back condition, the target was any letter identical to the immediately preceding one (i.e. one trial back). In the 2-back condition, the target was any letter that was presented two trials back. Thus, working memory load was varied from 0- to 2-back. The visual stimulus lists were pseudo-random sequences of letters (randomly varying in case). Subjects responded to each stimulus by pressing one button with their right hand for targets and the left hand for non-targets (0-back, 67 targets; 1-back, 64 targets; 2-back, 65 targets out of a total of 200 stimuli). The use of left/right hand to targets/non-targets was counterbalanced across subjects. In each sequence, a number of stimuli were non-target repeats that were included as foils (such as 1-back repeats occurring in the 2-back condition).

2.3. Stimuli

The visual stimuli were generated and presented using the NeuroScan Stim (v.3.0) system. The visual stimuli were presented through a television monitor. The letters were white and the background was black. There was a total of 25 letters (all consonants) displayed randomly in uppercase (e.g. X, mean height 11.8 cm) and lowercase (e.g. x, mean height 9.9 cm).

2.4. Experimental procedure

Following electrode placement and instrument calibration, the subject was seated in a comfortable chair in the 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 television screen placed in front of him/her (1.5 m) and to avoid unnecessary eye movements. The behaviour of the subject was observed on a television monitor throughout the experiment. The subjects were instructed to respond as fast and as accurately as possible to each stimulus by pressing one button for targets and another for non-targets. The following stimulus was shown 2000 ms after the subject had given his/her answer on the response pad. The length of a single memory-load experimental condition was 10 min (plus response time) and there were 200 trials in each memory-load experimental condition. The order of the three memory load conditions was counterbalanced between the subjects. Each subject performed each memory-load experimental condition twice, one with EMF on and one with EMF off. The total duration of the session was hence

~60 min. Between each memory-load experimental condition, the researcher entered the registration room to give further instructions to the subjects. A short break (~5 min) was provided as a rest for the subjects between the experimental conditions.

2.5. EMF procedure

Each EEG registration was subdivided into two segments, one with the EMF turned off and the other with the EMF turned on. The EMF exposure order was counterbalanced across the subjects, with the EMF active in the first segment for half of the subjects, and vice versa for the other half. The presence or absence of the EMF was unnoticeable for the subjects (single-blind condition).

A standard GSM phone was mounted to the subject's head over the right posterior temporal region, comparable to normal use, during both experimental conditions (EMF off and on). Normal new batteries were used and charged for full power. The normal battery life was 30 min for full power. The antenna was located ~20 mm from the skin. The electromagnetic field was a 902 MHz electromagnetic field pulsed with a frequency of 217 Hz and a pulse width of 0.557 ms. The phone was adjusted to send a maximum peak output power of 2 W. One time slot was used and the average power was $2\text{ W}/8 = 0.25\text{ W}$ (mean net forward power of the aerial). According to the manufacturer (Nokia) the SAR was well below 2 W/kg. The phone was operated via a computer from an adjacent room with the help of an extension lead, so that the subjects were not informed about the experimental condition (EMF off or on).

2.6. Recording

Twenty Ag/AgCl electrodes (Siemens-Elema) were placed bilaterally on the subject's scalp using electrode glue and the 10/20 system of electrode placement. Two EOG (electrooculogram) electrodes were placed on the outer side of the eyes to monitor for eye movement artefacts. All electrodes were referred to linked mastoids, which also served as the ground electrodes. The data were recorded using a sampling rate of 200 Hz.

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 0.3–70 Hz. The impedance of recording electrodes was monitored for each subject with a Braintronics electrode impedance meter before data collection and it was always $< 5\text{ k}\Omega$. The presence of an adequate EEG signal was determined by visual

inspection of the raw signal on the computer screen. During data gathering, the ongoing EEG data file was triggered with unique codes separately for targets and non-targets and the subjects' responses to these. These triggers were later used for off-line EEG and behavioural data analyses.

2.7. Data processing

The digital EEG data were band-pass filtered with linear FIR (Finite Impulse Response) filters in the following four frequency bands of interest: 4–6, 6–8, 8–10 and 10–12 Hz. To obtain a signal proportional to the power of the EEG frequency band, the filtered signal samples were squared. Thereafter, the data were epoched using a time window of 1500 ms. Three types of epochs were obtained for each block: intra-experimental reference interval (1500 ms preceding each stimulus presentation), non-targets (1500 ms) and targets (1500 ms). The EOG electrodes were used for artefact detection and epochs exceeding $100\text{ }\mu\text{V}$ were rejected.

After excluding epochs with artefacts, an average of 60, 52 and 35 trials/subject/non-target and 30, 25 and 18 trials/subject/target of event-related EEG data with epochs of 1500 ms remained for data analysis for the 0-, 1- and 2-back conditions respectively.

The mean power in the intra-experimental reference interval was assigned to 0% from which the relative power decrease (ERD, negative) or increase (ERS, positive) was calculated separately for non-targets and targets, separately for the three memory-load experimental conditions: 0-, 1- and 2- and the two EMF conditions (EMF off and on). Positive ERD/ERS indicate a relative power increase whereas negative ERD/ERS denote a relative power decrease as a response to a stimulus as compared to the power in the intra-experimental resting interval.

The data were averaged over left and right hemisphere electrode locations and these values were used in the statistical analyses (left hemisphere electrodes: O1, T5, P3, T3, C3, F3, F7; right hemisphere electrodes: O2, T6, P4, T4, C4, F4, F8).

2.8. Statistical analyses

Statistical analyses were conducted separately for each frequency band. The data were log-transformed to achieve a normal distribution. The data were thereafter entered into an analysis of variance for repeated measures with the following within-subject factors: EMF (two levels: on, off), TIME (15 levels: 1500–1000 ms), STIMULUS (two levels: non-target,

target), MEMORY LOAD (three levels: zero, one, two) and HEMISPHERE (two levels: left, right).

Factors with three or more levels carry an assumption known as sphericity or circularity (Vasey and Thayer 1987). Violation of this assumption results in positively biased tests. One method to compensate for this bias is to adjust the degrees of freedom using the Huynh–Feldt procedure. When appropriate, this procedure was always used to compensate for non-sphericity. Only corrected degrees of freedom, F and p are reported. Additionally, only results involving EMF will be discussed.

3. Results

All subjects performed well in the task. Table 1 displays the mean number of errors for the six experimental conditions. The main effect for the factor EMF on the error rate was not significant ($F < 1$). The differences in error rates between the three memory load conditions (0-, 1- and 2-back) were statistically significant ($F(2, 22) = 68.231$, $p < 0.001$), showing increasing task difficulty with increasing memory load. The EMF $\times$ memory load interaction was not significant ($F(2, 22) = 1.075$, $p > 0.1$).

The mean reaction times (RT) for the six experimental conditions are displayed in table 1. The main effect for the factor EMF on RT was not significant ($F < 1$). The differences in RT between the three memory load conditions were found to be statistically significant ($F(2, 22) = 38.931$, $p < 0.001$), revealing increasing latencies with increasing memory load. The EMF $\times$ memory load interaction was not significant ($F < 1$). These findings demonstrate that EMF in itself did not have any effect on either accuracy or RT.

The results for the four EEG frequency bands will be presented separately. Mean ERD/ERS values are displayed in the figures 1–4. Owing to computational problems the number of subjects between the analyses varies. Only results involving the factor EMF will be presented.

Table 1. Mean number of errors and reaction times (RT).

RF	Memory load	Errors (SD)	RT (SD)
Off	0	4.2 (3.4)	0.476 (0.106)
Off	1	6.2 (4.2)	0.688 (0.295)
Off	2	18.5 (9.6)	1.156 (0.499)
On	0	4.1 (4.4)	0.499 (0.118)
On	1	5.3 (3.6)	0.775 (0.264)
On	2	21.8 (9.4)	1.203 (0.528)

3.1. 4–6 Hz frequency band ($n = 17$)

As can be seen in figure 1, this frequency band showed differences between the ERD/ERS responses elicited by targets and non-targets but there were no visible effects of EMF on the ERD/ERS responses. Accordingly, the main effect for the factor EMF failed to reach the level of significance ($F(1, 16) = 1.47$, $p > 0.1$). All higher-level interactions involving the factor EMF also failed to reach the level of significance in this frequency band.

3.2. 6–8 Hz frequency band ($n = 21$)

In contrast to the ERD/ERS responses of the 4–6 Hz frequency band, the differences between the responses elicited by targets and non-targets were of smaller magnitude than those observed in the 4–6 Hz frequency band. An inspection of figure 2 reveals that the differences between the ERD/ERS responses elicited by targets and non-targets were smaller while EMF was on than when EMF was off. This effect was most apparent in the left hemisphere electrodes. Although the main effect for the factor EMF failed to reach significance ($F(1, 20) = 0.02$, $p > 0.1$), the STIMULUS $\times$ HEMISPHERE $\times$ EMF interaction did reach the level of significance ($F(1, 20) = 6.01$, $p < 0.05$).

3.3. 8–10 Hz frequency band ($n = 17$)

Although the main effect for EMF was not significant ($F < 1$) in this frequency band, the presence of EMF enhanced and delayed the ERD responses beginning at ~ 500 ms after stimulus presentation. This increase in ERD was most prominent for targets especially in the 0- and 1-back experimental conditions. In contrast, in the 2-back experimental condition, with EMF on, the early ERS (~ 100 – 300 ms after stimulus onset) was enhanced especially during the presentation of non-targets (figure 3). Owing to these observations, the LOAD $\times$ EMF ($F(1, 35) = 8.25$, $p < 0.01$), TIME $\times$ STIMULUS $\times$ EMF ($F(14, 97) = 2.83$, $p < 0.05$) and TIME $\times$ LOAD $\times$ EMF ($F(28, 105) = 2.56$, $p < 0.05$) interactions reached the level of significance.

3.4. 10–12 Hz frequency band ($n = 16$)

The effects of EMF on the ERD/ERS responses were modest in this frequency band (figure 4). Although figure 4 proposes that the presence of EMF altered the ERD/ERS responses, especially during the presentation of targets, the main effect for the factor EMF was not significant ($F < 1$) and neither

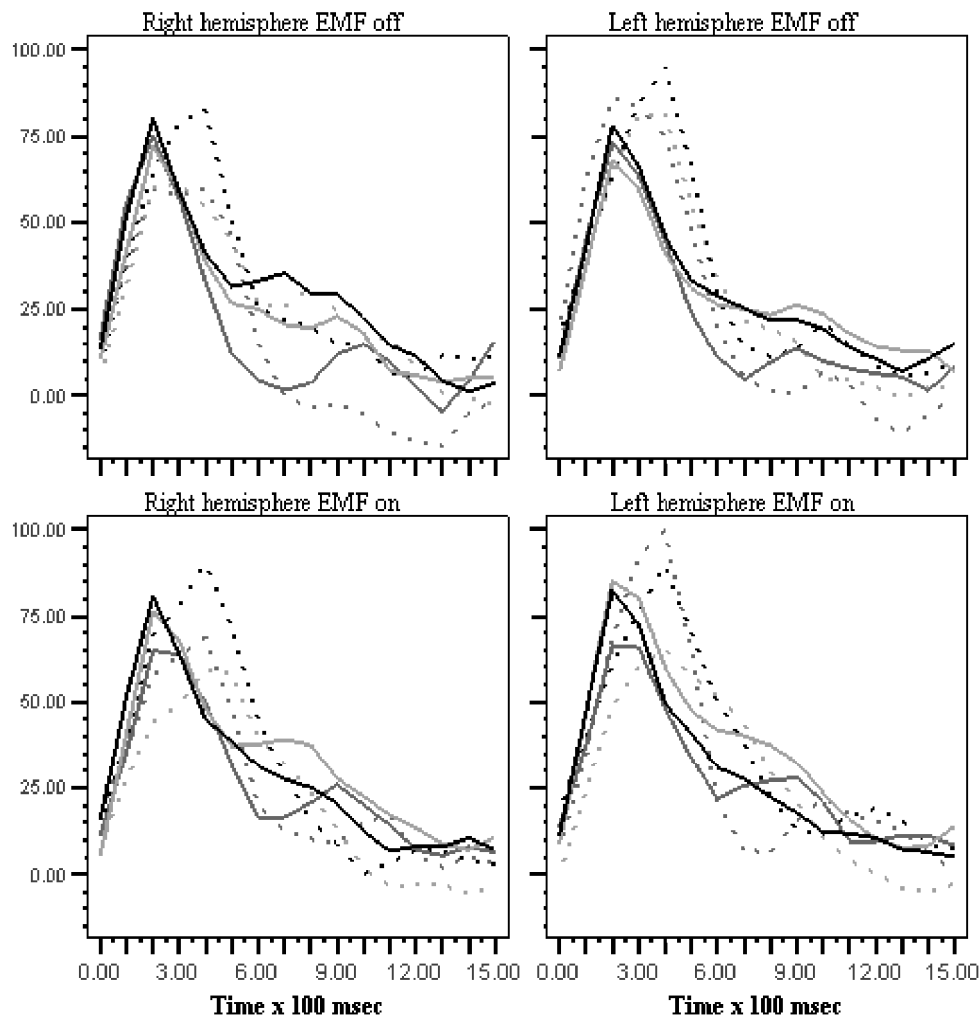


Figure 1. Mean ERD/ERS for the 4–6 Hz frequency band as a function of time, EMF (off, on), stimulus (non-target, solid line; target, scattered line), hemisphere (left, right) and memory load (0-back, black; 1-back, light grey; 2-back, dark grey). The y-axis displays the ERD/ERS. Positive values denote ERS whereas negative values stand for ERD.

were any of the higher-level interactions involving the factor EMF.

4. Discussion

To study the effects of EMF on brain electric oscillatory activity as a function of memory load, the event-related desynchronization and synchronization (ERD/ERS) responses of several narrow EEG frequency bands were examined while 24 subjects performed a visual sequential letter task in which memory load was varied from 0 to 2. The present results give further support for the assumption that GSM phones have effects on brain electric oscillatory activity ~ 8 Hz in particular during cognitive processing (Krause *et al.* 2000).

The main effect for the factor EMF failed to reach the level of significance in all studied frequency

bands. This finding is in line with Krause *et al.* (2000): the exposure to EMF seems to alter the EEG ERD/ERS responses only when examined as a function of cognitive task.

It was observed that in the 6–8 Hz frequency band, the exposure to EMF decreased the differences between the ERD/ERS responses elicited by targets and non-targets. Also in a recent study conducted by Krause *et al.* (2000), it was observed that the presence of EMF altered the ERD/ERS responses of this specific EEG frequency band but during retrieval from memory only (and not during encoding). Krause *et al.* (2000) reported that the differences between the ERD/ERS responses elicited by memory encoding and retrieval were less obvious when EMF was on than when EMF was off. It appears as if the presence of EMF would decrease the differences in cortical activity between different experimental conditions

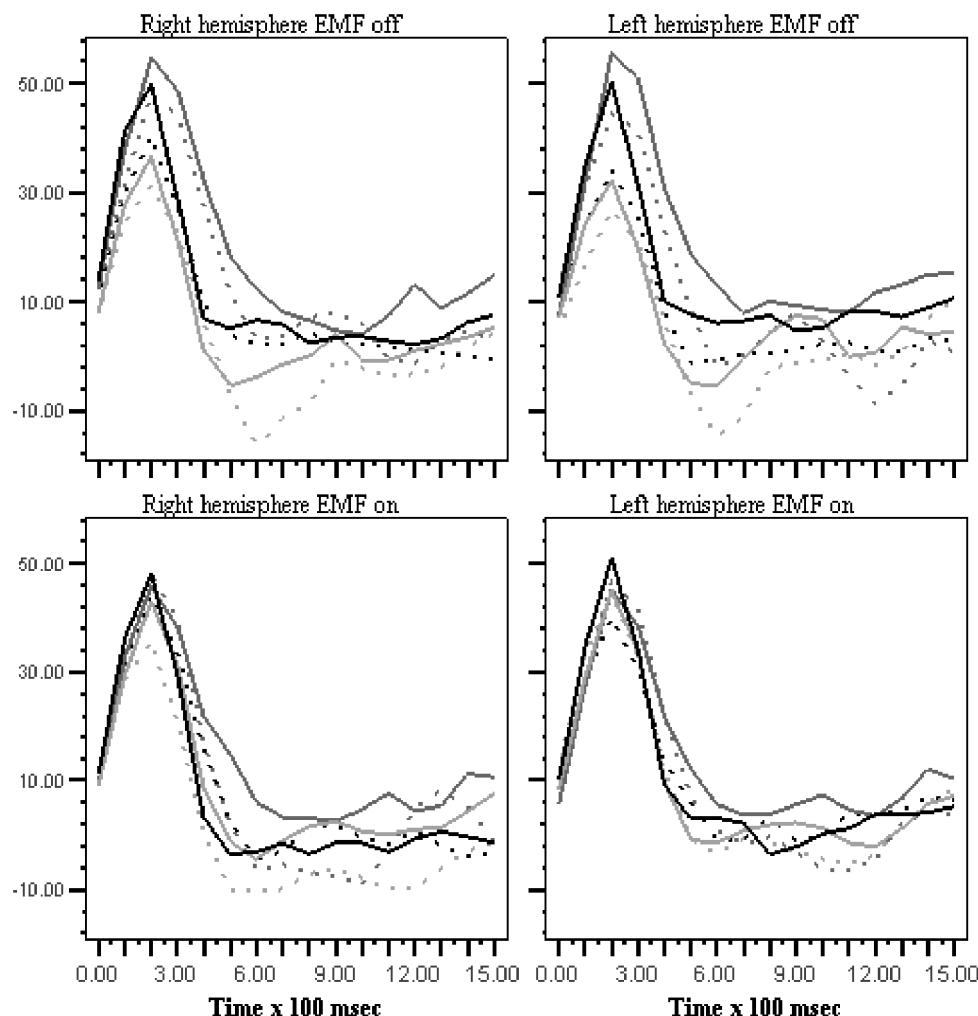


Figure 2. Mean ERD/ERS for the 6–8 Hz frequency band as a function of time, EMF (off, on), stimulus (non-target, solid line; target, scattered line), hemisphere (left, right) and memory load (0-back, black; 1-back, light grey; 2-back, dark grey). The y -axis displays the ERD/ERS. Positive values denote ERS whereas negative values stand for ERD.

(cognitive tasks) as measured by the ERD/ERS responses in brain electric oscillatory activity, especially ~ 8 Hz. In the present study, this effect was most apparent in the left hemisphere electrodes. However, the GSM phone was always attached to the right side of the subject's head. We are aware that further tests will be needed to resolve the possible cause for this finding.

In the 8–10 Hz frequency band, the presence of EMF enhanced and delayed the ERD responses especially after the presentation of targets mainly in the 0- and 1-back experimental conditions. In the 2-back experimental condition, the presence of EMF enhanced the early ERS appearing at 100–300 ms after the presentation of non-targets. Also, Krause *et al.* (2000) reported of effects of EMF on the 8–10 Hz EEG frequency band, especially during memory retrieval such that the early ERS was

enhanced and the later appearing ERD was delayed. Thus, the present findings are well in line with previous findings on the effects of EMF on brain electric oscillatory activity during cognitive processing. EMF seems to have significant effects on brain electric oscillatory activity ~ 8 Hz specifically during cognitive processes. Additionally, the present findings also give support for the reliability of the ERD/ERS method (Burgess and Gruzelier 1996): we reproduced similar effects of EMF on the ERD/ERS responses of the four studied frequency bands as reported (Krause *et al.* 2000). Although Krause *et al.* (2000) examined the effects of EMF on the ERD/ERS responses while the subjects performed an auditory verbal memory task, the present effects of EMF on the ERD/ERS responses (our subjects performing a visual working memory task) were consistent with those of Krause *et al.* (2000).

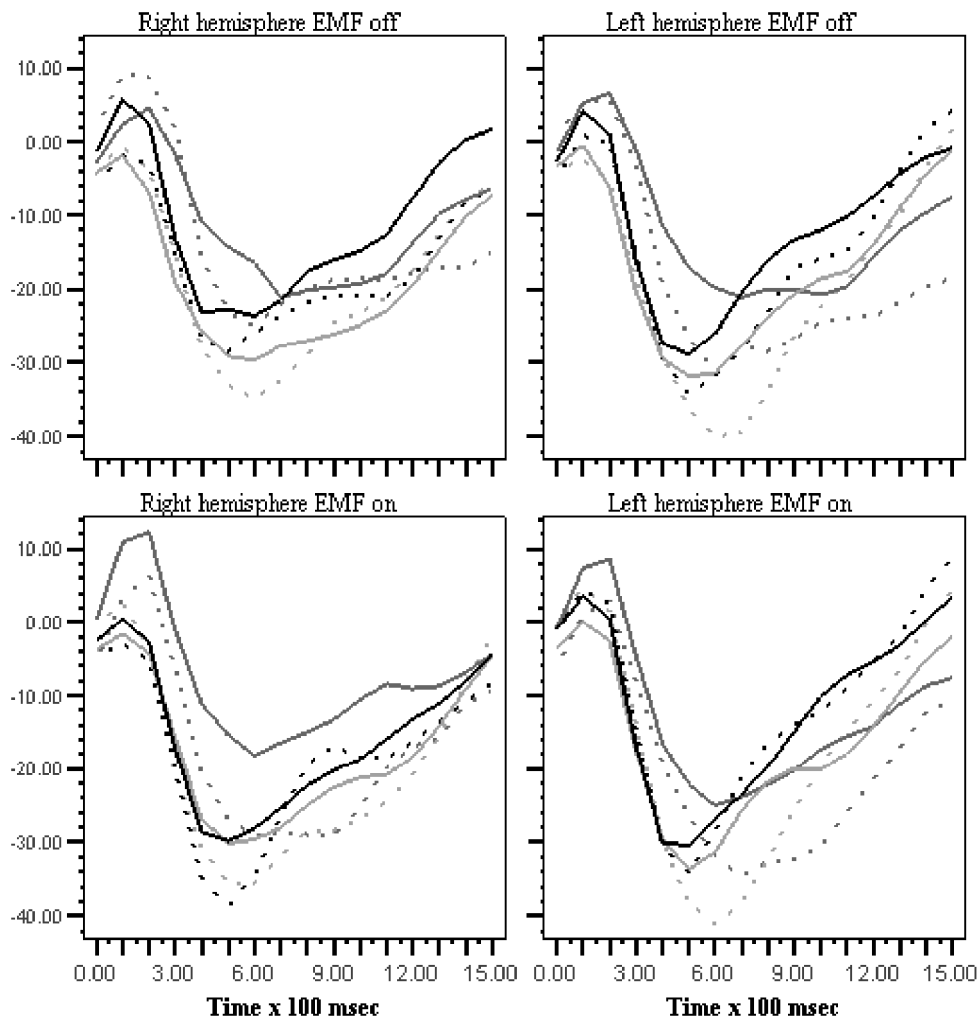


Figure 3. Mean ERD/ERS for the 8–10 Hz frequency band as a function of time, EMF (off, on), stimulus (non-target, solid line; target, scattered line), hemisphere (left, right) and memory load (0-back, black; 1-back, light grey; 2-back, dark grey). The y -axis displays the ERD/ERS. Positive values denote ERS whereas negative values stand for ERD.

Therefore, the effects of EMF on brain electric oscillatory activity might not be modality or task-specific.

In behavioural experiments, the exposure to EMF has been reported to decrease reaction times (Preece *et al.* 1999, Koivisto *et al.* 2000), suggesting that cellular phones may have a facilitatory effect on cognitive functioning. Although we observed no significant effect of EMF either on error rate or on reaction times, the alterations in the ~ 8 Hz ERD/ERS responses due to the exposure to EMF suggest that EMF might have effects on cortical oscillatory systems mediating e.g. attention (Klimesch *et al.* 1992, Krause *et al.* 2000).

It has been reported that the exposure to EMF would result in an enhancement of α power in the electroencephalogram (Mann *et al.* 1996). In that study, the effects of the EMF on the EEG were

examined over 8 h during sleep. In contrast, Wagner *et al.* (1998) could not reproduce such findings: they observed no alterations of the EEG rhythms during long-term (8 h) EMF exposure. Neither were Rösche *et al.* (1997) able to report of any alterations in the awake EEG during short-term exposure (3.5 min) to EMF as compared with that during no exposure. In these cited studies, however, no cognitive activity was included. The effects of EMF on brain electric activity during cognitive processing has been examined, e.g. by Freude *et al.* (1998), who observed that exposure to EMF exposure elicited a significant decrease in slow brain potentials. Additionally, Eulitz *et al.* (1998) reported that EMF exposure altered the normalized spectral power in the 18.75–31.25 Hz EEG frequency band range, however, for task-relevant items (targets) only. Although the differences in experimental conditions and EEG quantification

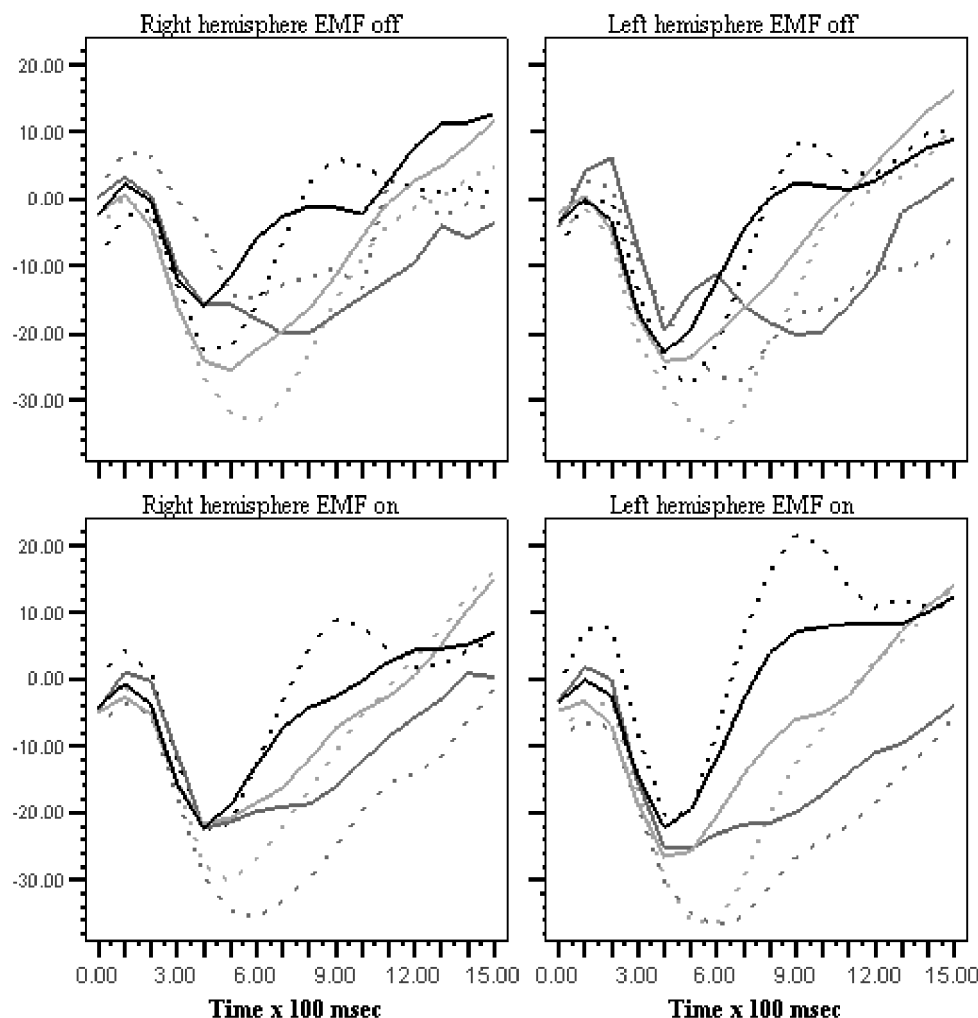


Figure 4. Mean ERD/ERS for the 10–12 Hz frequency band as a function of time, EMF (off, on), stimulus (non-target, solid line; target, scattered line), hemisphere (left, right) and memory load (0-back, black; 1-back, light grey; 2-back, dark grey). The y -axis displays the ERD/ERS. Positive values denote ERS whereas negative values stand for ERD.

methods in the cited studies are noticeable, the findings from the present study are in line with the results of these latter cited studies such that the effects of the exposure to EMF on the EEG might be most clearly distinguished during cognitive processes (Eulitz *et al.* 1998, Freude *et al.* 1998, Krause *et al.* 2000).

The exact physiological mechanisms mediating EMF effect on the ERD/ERS responses of certain EEG frequency bands remain open. It has been proposed that the application of EMF could result in mild cortical temperature changes that might affect synaptic transmission (Preece *et al.* 1999). Such conclusions remain, however, rather speculative and special experiments will be needed to assess such issues. Additionally, the relationships between the effects of EMF on brain and behaviour will need further testing.

To conclude, it is suggested that exposure to EMF seems to have effects on neural oscillatory systems ~ 8 Hz especially during mental processes requiring attention. The present results do not, however, allow any conclusions concerning the possible effects of cellular phone use on cognition.

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