

Effects of Pulsed and Continuous Wave 902 MHz Mobile Phone Exposure on Brain Oscillatory Activity During Cognitive Processing

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The aim of the current double-blind studies was to partially replicate the studies by Krause et al. [2000a,b, 2004] and to further investigate the possible effects of electromagnetic fields (EMF) emitted by mobile phones (MP) on the event-related desynchronisation/synchronisation (ERD/ERS) EEG (electroencephalogram) responses during cognitive processing. Two groups, both consisting of 36 male participants, were recruited. One group performed an auditory memory task and the other performed a visual working memory task in six exposure conditions: SHAM (no EMF), CW (continuous wave EMF) and PM (pulse modulated EMF) during both left- and right-side exposure, while the EEG was recorded. In line with our previous studies, we observed that the exposure to EMF had modest effects on brain oscillatory responses in the alpha frequency range (~8–12 Hz) and had no effects on the behavioural measures. The effects on the EEG were, however, varying, unsystematic and inconsistent with previous reports. We conclude that the effects of EMF on brain oscillatory responses may be subtle, variable and difficult to replicate for unknown reasons. *Bioelectromagnetics* 28:296–308, 2007. © 2007 Wiley-Liss, Inc.

Key words: EEG; ERD/ERS; EMF; memory

INTRODUCTION

Mobile phones (MP) emit ultra high-frequency electromagnetic fields (EMF) around them when in use. The close proximity of a MP to the user's head leads to the absorption of part of the EMF into the head and the brain [Schönborn et al., 1998]. Because MP usage has considerably increased during the last years, concerns have been expressed about how such ultra high-frequency EMF affects the human body and particularly, the brain and cognitive functioning [for reviews see Repacholi, 2001; Hamblin and Wood, 2002; Hossmann and Hermann, 2003].

Conflicting effects of EMF on human cognitive functioning have been recorded using behavioural measures: Some research groups have reported decreased reaction times [Preece et al., 1999; Koivisto et al., 2000a,b] and others have shown positive effects of EMF on cognitive performance [Smythe and Costall, 2003]. However, not all EMF studies have been able to demonstrate or replicate such behavioural effects [Freude et al., 1998; Haarala et al., 2003b, 2005; Besset et al., 2005].

The same holds true for psychophysiological EMF studies using the EEG (electroencephalogram):

both positive [Mann and Roschke, 1996; Eulitz et al., 1998; Freude et al., 1998, 2000; Borbely et al., 1999; Huber et al., 2000, 2002, 2003; Lebedeva et al., 2000; Krause et al., 2000a,b, 2004; Croft et al., 2002; Kramarenko and Tan, 2003; Hamblin et al., 2004; Hinrichs and Heinze, 2004; Loughran et al., 2005; Charalabos et al., 2006] and negative [Röschke and Mann, 1997; Wagner et al., 1998, 2000; Bak et al., 2003; Oysu et al., 2005; Hamblin et al., 2006; Yuasa et al., 2006] reports exist.

Additionally, whereas some recent studies have reported EMF effects on regional cerebral blood flow

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(rCBF) [Huber et al., 2002, 2005; Aalto et al., 2006], Haarala et al. [2003a] were not able to show such effects on brain metabolism as measured by positron emission tomography (PET).

The reason for variation and inconsistencies in the research results concerning MP effects on the brain and behaviour remains unclear. One possible explanation for the variation in reported results may be the variation in study design and methodology. The noteworthy, variation in several experimental aspects, for example EMF exposure side, EMF exposure systems and set-ups as well as experimental task variables in the EMF studies may have at least partially contributed to some of the variation and inconsistencies in the results.

The rhythmic, ongoing EEG activity is caused by minor currents of the neural activity and reflects brain activity. Due to its relatively good temporal resolution, the EEG provides a suitable method to examine neural correlates of fast and dynamic aspects of cognitive processes, such as working memory. The continuous EEG can be decomposed into oscillatory components by a number of means, such as wavelet analysis, which allows the inspection of the EEG signal as a function of both time and frequency [e.g. in Basar et al., 2001b].

Dynamic and distributed brain oscillatory systems have been proposed to act as the neural communication mechanism which mediates higher-level information processing [Klimesch, 1996, 1997, 1999; Klimesch et al., 1997; Basar, 2005]. The functioning of such distributed, dynamic neural processes underlying mental processes can be assessed by means of studying brain oscillatory responses at different frequencies while the subjects are engaged in cognitive processing. Recording of cognition- or memory-related EEG oscillatory responses serves as an excellent tool for measuring the dynamic neural correlates of these mental capacities. This is one of the few methods currently available that can assess distributed and dynamic brain processes during experiments on conscious individuals [Basar, 2005].

It is now acknowledged that human scalp recorded EEG oscillatory responses at different frequencies can be associated with several distinct aspects of cognitive functioning ranging from stimulus processing, attention, working memory, encoding and recognition to long-term memory [Krause et al., 1995, 1996; Basar et al., 1999, 2001a; Klimesch, 1999; Ward, 2003]. For example, responses in the theta frequency band (typically defined as $\sim 4\text{--}7$ Hz) have been related to encoding and recognition of information [for a review see Klimesch, 1999], memory-load demands [Krause et al., 2000c] and lexico-semantic processing [Bastiaansen et al., 2005]. Alpha frequency

($\sim 7\text{--}13$ Hz) responses have been associated with 'alertness' and attention [Klimesch et al., 1992] as well as semantic memory processes [Klimesch, 1994, 1996; Klimesch et al., 1998; Doppelmayr et al., 2000]. Beta frequency (~ 20 Hz) responses were first associated with the activity of motor cortices in relation to movement [Stancak and Pfurtscheller, 1996; Pfurtscheller et al., 1998], movement planning [Kaiser et al., 2001; Alegre et al., 2003] and motor imagery [Pfurtscheller and Neuper, 1997] but recently beta rhythm responses have also been reported in association with cognitive and linguistic processing [Weiss and Rappelsberger, 1996, 1998; Pulvermuller et al., 1999; Tallon-Baudry, 2003; Karrasch et al., 2004; Kopp et al., 2004; Bastiaansen et al., 2005; Pesonen et al., 2006]. By studying brain oscillatory responses during cognitive processing, we can assess the temporal arrangement of the neural oscillatory networks contributing to the cognitive process.

Event-related oscillatory EEG responses can be quantified, for example, by means of the event-related desynchronisation (ERD)-method [Pfurtscheller, 1977; Pfurtscheller and Lopes da Silva, 1999]. In this method, a relative decrease in the power of a certain frequency band during stimulus processing (as compared to a no-stimulation reference) is called ERD, whereas the opposite, a relative increase in power is called event-related synchronisation (ERS) [Pfurtscheller and Lopes da Silva, 1999]. The ERD/ERS values are expressed as a percentage and are within-subject measures of relative changes in the EEG [Pfurtscheller and Lopes da Silva, 1999; Krause, 2003]. As is the case with the EEG, the ERD/ERS technique is also characterised by a relatively good temporal resolution and provides a suitable method to assess dynamic brain oscillatory responses during cognitive processing [Krause, 2003].

The aim of the present studies was to assess the effects of both continuous wave (CW) and pulse modulated (PM) EMF on human brain oscillatory responses during cognitive processing. Additionally, we investigated whether there would exist differences between left- and right-side EMF exposure. All these effects were studied using the same cognitive tasks as used in our previous reports [Krause et al., 2000a,b, 2004]. In two of the previous studies by Krause et al. [2000a,b], EMF effects were reported on the ERD/ERS responses in the ~ 8 Hz EEG frequency range. However, in a recent replication study [Krause et al., 2004] no such effects were recorded.

In the current studies, we partially replicated these auditory and visual studies in order to assess the consistency of the findings from these studies. Additionally, we extended the studies to examine the effects of SHAM, CW and PM exposure as well as

exposure side (left and right). To our knowledge, only one previous study exists in which the effects of both CW and PM exposure, as well as exposure side on behaviour, has been assessed [Russo et al., 2006]. In that behavioural study, no effects of any of the experimental parameters on the behavioural measures were recorded. To our knowledge, the current studies are the first to report on the effects of both CW and PM EMF on brain oscillatory EEG responses during both auditory and visual cognitive processing.

MATERIALS AND METHODS

Studies

Two separate studies were conducted; namely, one auditory memory task and one visual memory task. In both studies, the EEG data were gathered in a total of six exposure conditions CW, PM and SHAM, both during left- and right-side exposure. In both studies, behavioural responses (number of correct responses in the auditory memory task and reaction times in the visual working memory task) were also gathered, analysed and reported as a function of MP exposure and exposure side.

Subjects

In both experimental groups, data from 36 healthy, right-handed adult male volunteers were gathered. The mean age of the subjects in the auditory memory task was 23.6 years (SD 2.38 years) and in the visual memory task 22.9 years (SD 2.4 years).

Prior to testing, all subjects gave their written informed consent. All were native speakers of Finnish. The experiments were conducted according to the currently relevant laws and regulations concerning ethical guidelines for psychologists. These include Professional Ethics for Psychologists in the Nordic Countries (Finnish Psychological Association, 1998), the Decree on Health Insurance 1.11.1963/470, the Act on Health Care Professionals 28.6.1994/559 and the Act on National Person Registers of Health Care 9.6.1989/556.

Exposure Set-Up in Both Studies

In order to have complete control over all exposure parameters, a signal generator (SMIQ 06B, Rohde & Schwarz, München, Germany), and a linear power amplifier (AS0822-7, Milmega Ltd, Isle of Wight, UK) were used to provide the EMF instead of a regular MP. These were, in turn, connected with a 10-m cable to a Nokia 6110 MP antenna, so as to provide the same EMF output as the original phone. The phone was not operational and the battery was disconnected

from its machinery. In other words, the phone was used only as a dummy except for its antenna which was connected to the signal generator via a cable, to create the EMF.

In the CW condition, the generator was set to create a 902 MHz EMF with 0.25 W power. In the PM condition, the EMF was of the same frequency but the power was pulsed at a frequency of 217 Hz, with a pulse width of 0.577 ms and with a mean power of 0.25 W. Thus, the frequency and the power output were the same for both conditions; the only difference was in the modulation. In the SHAM exposure condition, all equipment was set-up in a similar fashion as in the CW and PM conditions, but the signal generator did not produce a signal. This ensured that the experimenter was blind to the condition, as the set-up appeared to be identical for all conditions (trained personnel's actions and equipment noise (the amplifier's fan makes a sound when on)).

The power output from the generator-amplifier set-up was monitored approximately every 2 weeks with a Hewlett-Packard 437B Power Meter to ensure a consistent power output. Similarly, the EMF head-set was occasionally tested (spot check fashion) to ensure the existence of an EMF.

The signal generator and the power amplifier were located in a room adjacent to the room from where the subjects performed the tests. During the EEG recording, the subject was seated in a comfortable chair approximately 1.6 m from the computer screen where the stimuli were presented. A two-button mouse was used to respond to the stimuli. The background radiation of the laboratory in the frequency range of 10 Hz–20 kHz was measured to be less than 400 nT.

The dummy phone was attached to the subject's head using an earmuff, in which one of the protectors was replaced with the dummy MP. The phone was positioned as in normal use. The antenna (the source of the EMF) was located approximately 20 mm from the posterior temporal lobe of the subject in the left-side exposure, and over the inferior and posterior temporal lobe in the right-side exposure. The difference between the exposure sides was due to the asymmetrical position of the antenna. The SAR was measured with a SPEAG's Dosimetric Assessment System 4 (DASY4, Schmid and Partner Engineering AG, Zürich, Switzerland), and an adult generic twin phantom filled with 900 MHz head tissue simulating liquid ($\sigma = 0.97$ ohm/m, $\epsilon_r = 41.5$). The SAR value averaged over 1 g of tissue was 1.1 W/Kg (over 10 g 0.738 W/kg), and the measured peak value was 1.18 W/kg.

This set-up, described here as EMF head-set, was originally designed and built by Preece et al. [2005] who donated one of the set-ups for our studies. This was

then used as a model to build two additional head-sets. The EMF head-set was constructed using plastic and rubber and did not contain any metal parts.

EMF Procedure

In both experiments, a double-blind protocol was used, that is, the investigator and subjects were not informed of the presence or absence of the EMF. To ensure the experimenter was unaware of the exposure condition, all of the equipment displays but one were covered. On the amplifier, there is a LED-display which lights up if the power feed does not go through to the antenna of the EMF head-set. This was the only display that was not covered from the experimenter, so that she would be able to interrupt the testing in case of technical problems with the exposure equipment. Two people outside the project were first instructed how to operate the signal generator and the power amplifier. They were then given detailed written instructions for each test session describing how to inspect the equipment and set the correct exposure condition. When the experimenter was ready to begin a testing session, she would tell one of these trained personnel which setting, A, B or C, she would require for that session. One of the trained personnel would then follow the written instructions to set that particular setting, and inform the experimenter when the exposure set-up was ready for testing. After the testing session, the experimenter would inform the trained personnel to shut down the signal generator and the power amplifier.

In both experiments, testing was conducted in three sessions according to EMF exposure condition; CW (continuous wave), PM (pulse modulated) and SHAM (no EMF). Each session was separated by 1 week. In each EMF exposure condition, both sides were exposed. The experimental condition order (both exposure condition and exposed side) was counter-balanced across the subjects, and the exposure side condition was further balanced across the exposure conditions. In both experiments, the exposure condition began when the cognitive task began, that is, the subjects were not exposed to any EMF before the experiment.

EEG Recording

In both experiments, the EEG was recorded using the 10/20 system Electrode-Cap (Electro-Cap International, Inc., <http://www.electro-cap.com>). Additionally, two EOG electrodes were sited on the outer side of the canthi and all electrodes were referred to right mastoid and an electrode attached to middle of head served as the ground electrode. The data were recorded using a sampling rate of 250 Hz. Raw EEG signals were recorded using the Neuroscan 386 Scan 4.1 data acquisition system with a Synamps amplifier with a

frequency band of 0.1–50 Hz. The impedance of recording electrodes was monitored for each subject with a Braintronics electrode impedance meter prior to data collection and was always below 5 k Ω .

Auditory Memory Task EEG Study

Stimulus materials and task. The stimuli were 24 auditorily presented Finnish verbs spoken by a female voice. The mean length of the stimuli was 6.7 phonemes (SD = 0.9) and the mean duration was 764 ms (SD = 81.7). The Neuroscan Stim system (ver. 3.0) was used to control the presentation of the auditory stimuli. The stimuli were presented through E-ARTONE ABR insert earphones (10 Ω) at a comfortable sound pressure level (~70 dB).

A modified version of Sternberg's memory search paradigm [Sternberg, 1966] was used. A total of 192 four-verb memory sets was constructed. Each memory set consisted of four auditorily presented Finnish verbs. The frame set size was kept constant and consisted of one verb (probe). Each of the memory sets was randomly drawn from the 24 verbs, with the restriction that each verb had to occur with equal frequency and only once in a single memory set. After 2000 ms following the presentation of the memory set, a fifth verb was presented to the subject. The subject then had to decide whether the fifth verb was among the previously presented four verbs.

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 TV screen placed in front of him (1.6 m) and to avoid unnecessary eye movements. The behaviour of the subject was observed on a TV monitor throughout the experiment.

Each trial began with a 3500 ms intra-experimental reference (no stimulation) condition. After this, a visual warning signal (a red spot), appeared for 100 ms on the TV screen. After 1500 ms, the four-verb memory set (memory encoding) was presented. Following an interval of 2000 ms the probe verb was presented (memory recognition). The subject then had to decide whether the probe verb had appeared in the memory set or not. Subjects responded to the stimuli using a hand-held response pad using their right hand. In an attempt to avoid muscle artefacts and motor artefacts, the subjects were asked to withhold their response until a visual warning signal (a green spot) appeared on the TV screen

1500 ms after the probe. The next trial started when the subject had given his answer on the response pad. The length of a single trial was 17 s (+ response time). In each exposure side condition, EEG data were gathered for about 27 min and the total length of one session was about 54 min (+ setting up and taking off the electrodes).

Data processing. The digital EEG data were processed in a MATLAB 6.5 environment. Time-frequency representations (TFRs) were calculated (Morlet wavelet, width 8), which display the power of the EEG signal as a function of time and frequency in the same matrix. TFRs of 1600 ms (−100 to 1500 ms from trigger) and 1–30 Hz were calculated for each subject, separately for each condition; for the no-stimulation reference interval (1600 ms EEG segment prior to the presentation of the memory set), for the four stimuli in the memory set and for the probe stimulus. Due to some inaccuracy at border points caused by the wavelet-analysis method, the initial time windows were selected to be longer than the actual time windows of interest. While displaying the final TFR-data, these inaccurate points were omitted, thus showing data at 0–1400 ms from stimulus onset.

Calculations were performed for each EEG channel separately. Artefact rejection was set to ± 70 μ V. Poor quality signal channels were excluded from further analyses by means of visual inspections of the TFRs displaying the absolute power values.

After artefact rejection, the power in the reference interval TFR was averaged over time. Thereafter, the relative differences (event-related desynchronisation and synchronisation, ERD/ERS) in EEG power between the averaged reference interval and the actual stimuli were calculated and expressed as a percentage. This resulted in ERD/ERS TFRs displaying, as percentage, the relative power differences between the reference interval and the actual stimuli as a function of frequency and time. While calculating the ERD/ERS values, the data were averaged to five electrode locations (Frontal Fp1 Fp2 F3 Fz F4, Left Temporal F7 T3 C3 T5, Right Temporal F8 T4 C4 T6, Parietal Cz P3 Pz P4, Occipital O1 O2).

The ERD/ERS TFRs for the four stimuli in each memory set and for the two probe conditions (included in the memory set, yes/no) were averaged separately for each individual and for all the experimental conditions. After these calculations, 12 ERD/ERS TFRs were obtained for each subject: encoding and recognition for the SHAM, CW and PM EMF exposure conditions and left- and right-side exposure.

In order to examine the data regardless of possible exposure side effects, the data were also averaged over

exposure sides, resulting in six ERD/ERS TFRs: encoding and recognition for the SHAM, PM and CW conditions.

Visual Memory Task EEG Study

Stimulus materials and task. The subjects performed a visual sequential letter memory task (n-back task). The visual stimuli (letters) were generated and presented using the NeuroScan Stim (ver. 3.0) system. The visual stimuli were presented on a TV monitor. The letters were white and the background was black.

The visual stimulus lists were pseudorandom sequences of letters (randomly varying in case) consisting of 120 stimuli (36 targets and 84 non-targets). The target letter was always in a different case from the probe letter. 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).

Experimental procedure. Electrode placement, instrument calibration and subject preparation and monitoring were exactly the same as previously described.

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. Subjects responded to the stimuli using a hand-held response pad in their right hand. In the 0-back condition, subjects responded to a single pre-specified target letter ('X'). In the 1-back condition, the target was any letter that was the same as the one immediately preceding (probe letter) it (i.e. one trial back). In the 2-back condition, the target was any letter that was presented two trials back and in the 3-back condition, any letter which was presented three trials back. Thus, working memory load was varied from 0 to 3. The following stimulus was shown 2500 ms after the subject had given his answer on the response pad. The length of a single memory-load experimental condition was 10 min (+ response time) and there were 120 trials in each memory-load condition. The order of the four memory-load conditions was counterbalanced between the subjects. Each subject performed each memory-load condition (4) with each EMF condition (3) and for both exposure sides (2). The total duration of one exposure side condition was about 40 min and the length of one session was about 80 min (+ setting up and taking off the electrodes).

Between each memory-load condition, the researcher entered the registration room to give further instructions to the subjects. A short break (about 5 min)

was provided as a rest for the subjects between the exposure side conditions.

Data processing. The digital EEG data were processed in a MATLAB 6.5 environment. TFRs were calculated (Morlet wavelet, width 8), which display the power of the EEG signal as a function of time and frequency in the same matrix. TFRs of 2600 ms (−600 to 2000 ms from trigger) and 1–30 Hz were calculated for each subject, separately for the six EMF conditions and for the no-stimulus reference interval (1000 ms EEG segment prior to the presentation of the stimulus), for the four memory-load conditions and for the targets and non-targets. The calculations were performed for each EEG channel separately. Artefact rejection was set to $\pm 100 \mu\text{V}$. Poor quality signal channels were excluded from further analyses by means of visual inspections of the TFRs displaying the absolute power values.

After artefact rejection, the power in the reference interval TFR was averaged over time. Thereafter, the relative differences in EEG power between the averaged reference interval and the actual stimuli were calculated and expressed as a percentage. This resulted in ERD/ERS TFRs displaying, as a percentage, the relative power differences between the reference interval and the actual stimuli as a function of frequency (1–30 Hz) and time (0–1800 ms). While calculating the ERD/ERS values, the data were averaged to five electrode locations (Frontal Fp1 Fp2 F3 Fz F4, Left Temporal F7 T3 C3 T5, Right Temporal F8 T4 C4 T6, Parietal Cz P3 Pz P4, Occipital O1 O2). Thereafter, the ERD/ERS TFRs for each stimulus (both targets and non-targets) were averaged separately for each individual and for all experimental conditions. After these calculations, 48 ERD/ERS TFRs were obtained for each subject: target and non-target in 0-back, 1-back, 2-back and 3-back conditions for the SHAM, CW and PM EMF conditions with left and right exposure side.

In order to examine the data regardless of possible exposure side effects, the data were also averaged over exposure sides, resulting in 24 ERD/ERS TFRs: target and non-target in 0-back, 1-back, 2-back and 3-back conditions for the SHAM, CW and PM EMF conditions.

Statistical Analyses for Both EEG Studies

The non-parametric Quade test was used to assess the statistical significance of the differences in the ERD/ERS TFRs between the experimental conditions, separately for each stimulus. The statistical computations were performed in the MATLAB 6.5 environment. The results from the Quade test were displayed as probability TFRs, in which any statistically significant

($P < .05$) effects were shown as a function of EEG frequency and time.

RESULTS

The EEG results were displayed as TFRs, in which the ERD/ERS values were shown as a function of time and frequency for five electrode locations (Fig. 1). The results from the statistical analyses were displayed as probability TFRs in which any statistically significant ($P < .05$) effects were displayed as a function of EEG frequency and time.

Due to the large amount of data analyses conducted, only the statistically significant MP or exposure side effects on the ERD/ERS values are reported.

Auditory Memory Task EEG Study

The mean ERD/ERS values during encoding and recognition are displayed in Figure 1. The different rows show the mean ERD/ERS values for the different exposure conditions: SHAM, CW and PM.

MP effects averaged over both exposure side conditions. In this analysis, the only statistically significant MP effect arose from the fact that during encoding, slightly greater ~ 8 Hz ERS responses were elicited during PM, whereas during recognition, smaller ~ 8 Hz ERD responses were witnessed during PM exposure, as compared to the CW exposure condition (Fig. 2).

MP exposure side effects. Differences between the ERD/ERS responses between the exposure sides were witnessed during the SHAM condition: During encoding, greater ~ 8 – 10 Hz ERS values were observed during left-side exposure than during right-side exposure. Also in the CW condition some effects emerged such that during encoding, greater ~ 10 – 15 Hz ERS responses were witnessed during right-side exposure and during recognition, greater ~ 10 Hz ERD responses were witnessed during left-side exposure (Fig. 3).

Visual Working Memory Task EEG Study

MP effects averaged over both exposure side conditions. In this analysis, differences between the ERD/ERS values emerged between the CW and PM conditions, such that greater magnitude ~ 8 – 12 Hz ERD responses were witnessed during the PM than during the CW exposure condition.

MP exposure side effects. No statistically significant effects of exposure side were witnessed in any of the MP conditions.

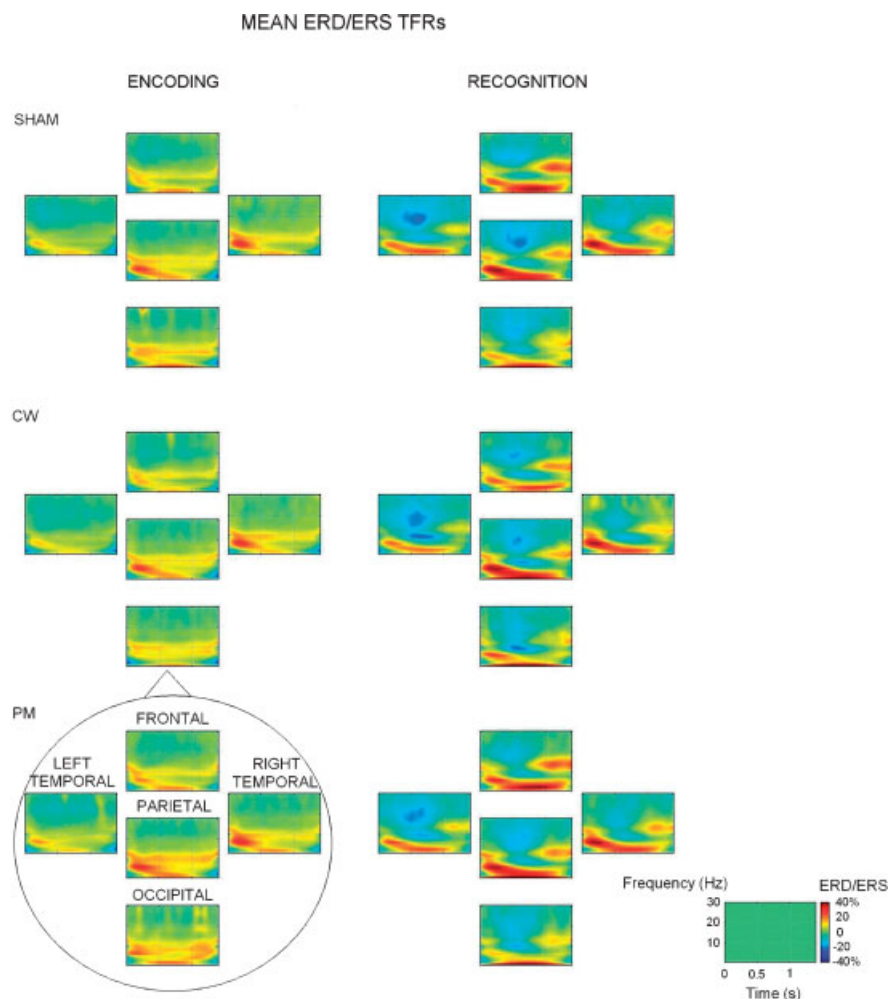


Fig. 1. Mean ERD/ERS TFRs (time–frequency representations) during the auditory memory task for five electrode locations (nose up: frontal, left temporal, right temporal, parietal and occipital), separately for the encoding and recognition stage. The first row displays the ERD/ERS values during the SHAM, the second row during the CW and the third row during the PM exposure condition. In all TFRs time (0–1400 ms after stimulus onset) is displayed on the x-axis and frequency (1–30 Hz) is displayed on the y-axis. The ERD/ERS colour scale ranging from –40% to +40% is depicted in the right lower corner.

Behavioural results. All behavioural data were analysed using the SPSS 11.0 software package. The mean percentages of correct answers for the different experimental conditions from the auditory and visual memory task are displayed in Table 1. The mean reaction times obtained in the visual memory task for all different experimental conditions are displayed in Table 2.

The behavioural data (percentage of correct answers) from the auditory memory task were entered into a 3×2 repeated measures analysis of variance with exposure (SHAM, CW, PM) and exposure side (left, right) as within-subjects factors. The main effects for

these factors (exposure $P = .825$; exposure side $P = .999$) failed to reach the level of statistical significance as did the exposure $\times$ exposure side interaction ($P = .894$).

Similarly, the data from the visual working memory task were entered into a $3 \times 2 \times 4$ repeated measures analysis of variance with the exposure (SHAM, CW, PM), exposure side (left, right) and memory load (0-, 1-, 2-, 3-back) as within-subjects factors. The main effects for the factors exposure ($P = .902$) and exposure side ($P = .948$) failed to reach the level of statistical significance. The main effect for the factor memory load was statistically significant

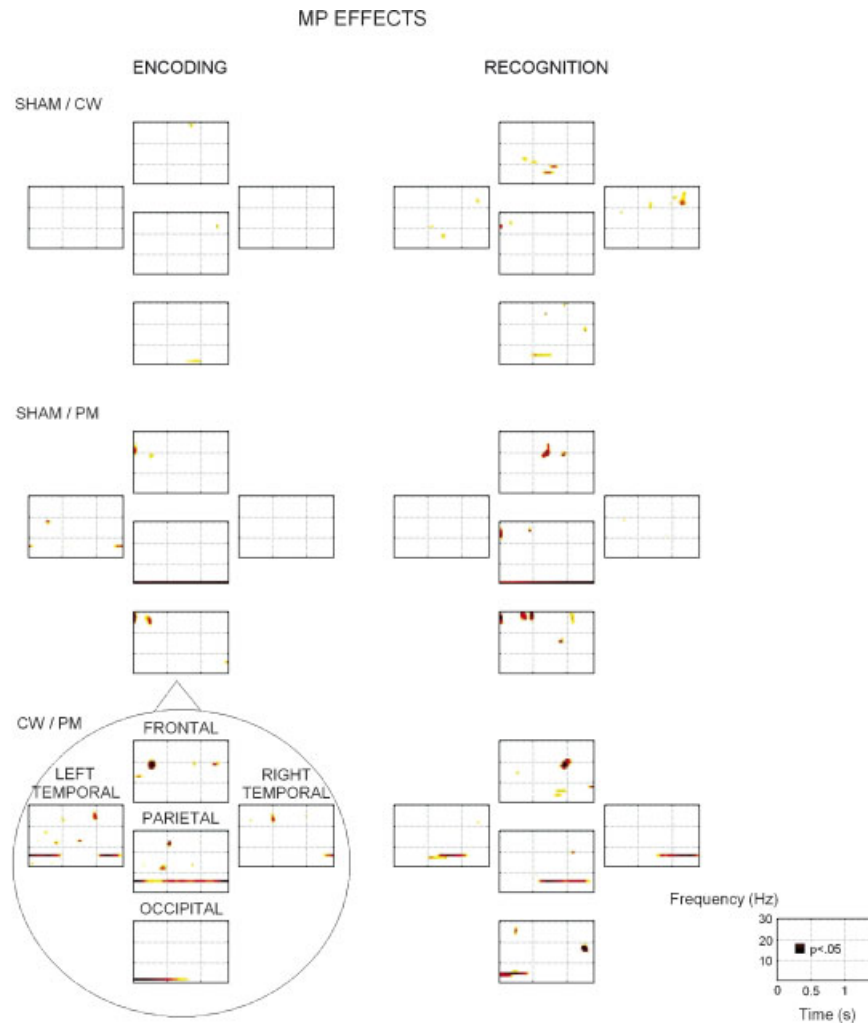


Fig. 2. ProbabilityTFRs (auditory memory task) in which statistically significant differences ($P < .05$) between the MP conditions are displayed for five electrode locations (nose up: frontal, left temporal, right temporal, parietal and occipital). The first row displays statistically significant points between the SHAM and CW condition, the second row between the SHAM and PM and the third row between the CW and PM exposure conditions. In all TFRs time (0–1400 ms after stimulus onset) is displayed on the x-axis and frequency (1–30 Hz) is displayed on the y-axis.

($P = .000$). However, none of the interactions between these factors reached the level of statistical significance ($P > .8$).

The mean RTs from the visual memory task EEG-study are represented in Table 2. These were entered into a $3 \times 2 \times 4$ repeated measures analysis of variance with the exposure (SHAM, CW, PM), exposure side (left, right) and memory load (0-, 1-, 2-, 3-back) as within-subjects factors.

The main effects for the factors exposure ($P = .847$) and exposure side ($P = .997$) failed to reach the level of statistical significance. The main effect for the factor memory load was statistically significant ($P = .000$). The interactions between these factors did not reach the level of statistical significance ($P > .7$).

CONCLUSIONS AND DISCUSSION

In the current studies, we investigated the effects of both CW and PM EMF on human cognitive function as measured by brain oscillatory responses during the performance of cognitive tasks. Furthermore, the effect of exposure side was also investigated.

We observed, in line with previous studies [Krause et al., 2000a,b] that the exposure to EMF modestly altered brain oscillatory responses especially in the alpha (~ 8 – 12 Hz) frequency range but had no effect on cognitive functions on the behavioural level. Further, the MP effects on the EEG ERD/ERS responses were varying, unsystematic and inconsistent. Our observations are discussed below.

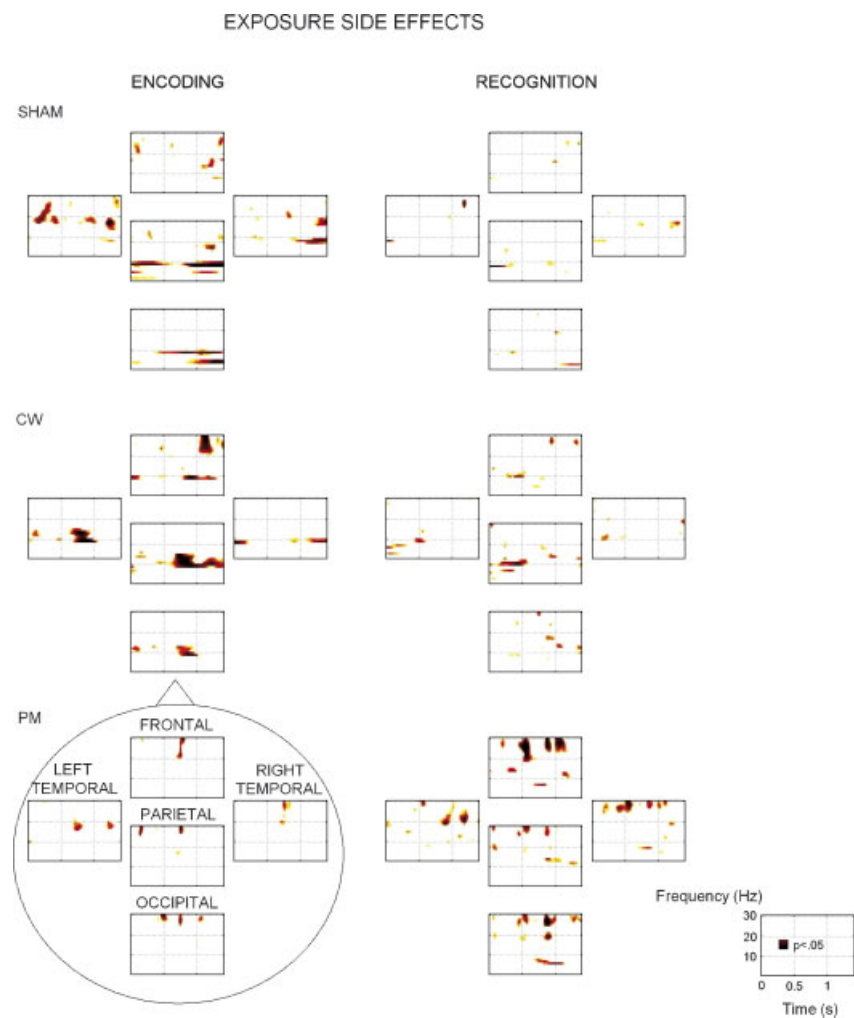


Fig. 3. ProbabilityTFRs (auditory memory task) in which statistically significant differences ($P < .05$) between the exposure side conditions are displayed for five electrode locations (nose up: frontal, left temporal, right temporal, parietal and occipital). The first row displays statistically significant points between exposure side conditions (left vs. right) in the SHAM, the second row in the CW and the third row in the PM exposure conditions. In all TFRs time (0–1400 ms after stimulus onset) is displayed on the x-axis and frequency (1–30 Hz) is displayed on the y-axis.

In the auditory memory task, the MP effects were modest and the only statistically significant effect arose between the PM and CW exposure conditions, such that greater alpha ERS and smaller alpha ERD responses

were recorded during the PM exposure condition as compared to CW exposure condition.

In the auditory memory task, exposure side effects were witnessed in the SHAM condition (encoding:

TABLE 1. Mean Percentage of Correct Answers (SD) in the Auditory and Visual Memory Tasks for Each EMF (SHAM, CW, PM) and Exposure Side (Left, Right) Condition

EEG-study	Sham		Continuous wave		Pulse modulated	
	Left	Right	Left	Right	Left	Right
Auditory memory task	93.8 (2.9)	93.4 (4.7)	93.2 (4.3)	93.4 (4.3)	93.0 (4.3)	93.3 (4.3)
Visual memory task, all	95.6 (3.7)	96.3 (3.8)	96.2 (4.1)	96.0 (4.5)	96.1 (3.8)	95.9 (4.1)
0-back	98.4 (1.7)	99.0 (1.0)	98.7 (5.5)	98.8 (1.3)	98.7 (1.4)	98.5 (2.2)
1-back	97.0 (1.8)	96.9 (2.6)	97.1 (1.9)	97.0 (1.9)	96.9 (1.9)	96.1 (3.6)
2-back	95.8 (3.3)	96.3 (2.7)	96.3 (3.3)	95.9 (4.0)	96.0 (3–6)	95.9 (3.6)
3-back	92.2 (4.1)	92.9 (5.0)	92.6 (3.3)	92.5 (6.3)	92.8 (4.8)	93.0 (4.7)

TABLE 2. Mean (SD) of Reaction Time (ms) in the Visual Memory Task EEG Study for Each Memory Load (0-, 1-, 2-, 3-back), EMF (SHAM, CW, PM) and Exposure Side (left, right) Condition

Task	Sham		Continuous wave		Pulse modulated	
	Left	Right	Left	Right	Left	Right
0-back	439 (130)	425 (96)	440 (98)	437 (109)	438 (104)	456 (156)
1-back	519 (167)	508 (175)	532 (149)	524 (183)	512 (150)	525 (145)
2-back	827 (457)	838 (456)	793 (354)	779 (321)	780 (317)	804 (334)
3-back	1358 (976)	1323 (888)	1434 (1026)	1357 (1087)	1245 (685)	1347 (873)
Average of all tasks	786 (653)	775 (617)	800 (669)	774 (675)	744 (498)	783 (590)

greater ~ 8 – 10 Hz ERS values during left side exposure than during right-side exposure). Currently, this observation remains without a logical explanation. Additionally, during right-side CW, greater alpha 10 – 15 Hz ERS responses emerged during encoding. During recognition, greater ~ 10 Hz ERD responses were witnessed during left-side exposure. These effects were subtle and unsystematic.

In the visual working memory task, the MP and exposure side effects were modest or non-existent. Some MP effects were witnessed between the CW and PM conditions: greater magnitude ~ 8 – 12 Hz ERD responses were witnessed during the PM than during the CW exposure condition. In the visual working memory task, no statistically significant effects of exposure side were witnessed.

MP exposure or exposure side had no effect on any of the behavioural measures; namely, number of correct answers or reaction times. This observation is in line with some other behavioural EMF studies [Freude et al., 1998; Haarala et al., 2003b, 2005; Besset et al., 2005].

The current studies are, to our knowledge, the first to look specifically at the effects of MP modulation and exposure side on the brain oscillatory responses during cognitive processing. Further, they are the first in which the EEG ERD/ERS responses of both lower (theta) and higher (beta) frequency bands were assessed during the exposure to EMF. However, no MP effects were witnessed in these lower or higher EEG frequencies.

Our observations need closer scrutiny. Although the effects were subtle and unsystematic, differences in the ERD/ERS responses were witnessed between the PM and CW exposure conditions, especially in the alpha (~ 8 – 12 Hz) frequency range. Several reports exist in which EMF has been reported to modify the EEG particularly in the alpha frequency range [Reiser et al., 1995; Borbely et al., 1999; Krause et al., 2000a,b; Huber et al., 2002; Curcio et al., 2005]. It may be the case that ultra-high-frequency EMF (i.e. oscillatory activity) emitted by MPs may directly interfere with brain electric oscillatory activity, especially in the alpha frequency range [Weinberger and Richter, 2002].

What are the physiological mechanisms causing such subtle EEG alterations during MP exposure? Some researchers have reported mild increases in head skin temperature [Paredi et al., 2001] when using a MP, perhaps also resulting in mild increases in cortical temperature [Preece et al., 1999]. However, the rise in brain tissue temperature beneath an active MP has been reported to be very small (fractions of $^{\circ}\text{C}$) and thus some research groups have suggested non-thermal EMF effects on brain tissue [for a review see Challis, 2005]. Schirmacher et al. [2000] reported that exposure to EMF had effects on the permeability of the blood brain barrier whereas Braune et al. [2002] did not observe any effects of EMF on cardiovascular and hormonal parameters of the autonomic nervous system. Some studies suggest that exposure to EMF may affect brain metabolism [Aalto et al., 2006]. In two studies, Huber et al. [2002, 2005] reported that PM EMF had effects on rCBF and suggested that pulse modulation may be crucial for EMF-induced alterations in brain physiology. The exact mechanisms on how EMF induces alterations in regional brain metabolism is still under investigation.

Although we were able to reproduce some of our previous findings [Krause et al., 2000a,b], the current results support the hypothesis that the possible effects of EMF on brain oscillatory systems during cognitive processing are very subtle. The EMF effects may be too small to be consistently observed and/or replicated with the EEG. If the differences found in the present studies are observations of an actual effect, they are far too subtle to be systematically replicated. Alternatively, the observed effects in the EEG can be a result of chance or confounding factors. These alternative explanations are viable in light of our results, according to which there were statistically significant differences between exposure side conditions, even during the SHAM exposure condition. It is difficult to argue that the change of an inactive MP from one side of the head to the other would produce observable effects on the brain oscillatory activity.

We conclude that EMF effects on the EEG are either non-existent or so susceptible to many other

factors in standard EEG experiments (such as normal variation in the EEG, attentional effects, random variance, etc.), that they are difficult to capture systematically.

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