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Mobile phone effects on children's event-related oscillatory EEG during an auditory memory task

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Abstract

Purpose: To assess the effects of electromagnetic fields (EMF) emitted by mobile phones (MP) on the 1–20 Hz event-related brain oscillatory EEG (electroencephalogram) responses in children performing an auditory memory task (encoding and recognition).

Materials and methods: EEG data were gathered while 15 subjects (age 10–14 years) performed an auditory memory task both with and without exposure to a digital 902 MHz MP in counterbalanced order.

Results: During memory encoding, the active MP modulated the event-related desynchronization/synchronization (ERD/ERS) responses in the ~4–8 Hz EEG frequencies. During recognition, the active MP transformed these brain oscillatory responses in the ~4–8 Hz and ~15 Hz frequencies.

Conclusions: The current findings suggest that EMF emitted by mobile phones has effects on brain oscillatory responses during cognitive processing in children.

Keywords: EEG, EMF, mobile phone, ERD/ERS, GSM, memory, children

Introduction

Cellular mobile phones (MP) emit high-frequency electromagnetic fields (EMF). The close proximity of a mobile phone to the user's head leads to the absorption of a part of the EMF into the head and brain (Schönborn et al. 1998). The possible effects of such fields on the human body, brain and health have recently been broadly studied and discussed (for a review, see e.g., Cook et al. 2002). Logically, due to the increasing MP usage, recently interest has arisen towards possible long-term MP usage effects, high-usage MP effects and MP effects on children (Maisch 2003). There are concerns that children may be more vulnerable to potential MP effects as their brains are still developing, their head size is smaller, and hence absorb more energy from EMF, and their exposure over lifetime will be greater (Maisch 2003).

The rhythmic, ongoing EEG (electroencephalogram) activity is caused by minor currents of 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 brain processes, e.g., during cognitive processing. The continuous EEG signal consists of oscillatory components at different frequencies and these can be studied by means of, e.g., wavelet analysis, which allows the inspection of the EEG signal simultaneously as a function of time and frequency (e.g., in Basar et al. 2001b). EEG oscillatory responses at different frequencies have been associated with distinct aspects of cognitive functioning ranging from stimulus processing, attention, working memory, encoding and recognition to long-term memory (Basar et al. 2000, 2001a, Klimesch 1999, Ward 2003, Basar 2005, Basar et al. 1999, Krause et al. 1996). For example, the

responses of the theta frequency band (typically defined as $\sim 4\text{--}8$ Hz) have been related to encoding and retrieval of information (for a review, see (Klimesch 1999)), memory load demands (Krause et al. 2000a) 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 et al. 1994, Klimesch 1997). Beta frequency (~ 20 Hz) responses were first associated with the activity of the motor cortices in relation to movement (Pfurtscheller et al. 1998, Stancak & Pfurtscheller 1996), movement planning (Kaiser et al. 2001, Alegre et al. 2003) and motor imagery (Pfurtscheller & Neuper 1997) but recently beta rhythm responses have also been reported in association with cognitive and linguistic processing (Tallon-Baudry 2003, Weiss & Rappelsberger 1996, Karrasch et al. 2004, 2006, Pulvermüller et al. 1999, Bastiaansen et al. 2005, Pesonen et al. 2006). Thus, by studying brain oscillatory responses during cognitive processing, one can assess the temporal arrangement of the neural oscillatory networks contributing to the cognitive process. It is also possible to study the effects of EMF on brain oscillatory responses during cognitive processing (Krause et al. 2000b, 2000c, 2004).

One way to assess event-related oscillatory EEG responses is the so-called event-related desynchronization method (ERD) (Pfurtscheller 1977). In this method, a relative decrease in the power of a specific frequency band during stimulus processing (as compared to a no-stimulation reference) is called event-related desynchronization (ERD), whereas the opposite, a relative increase in the power is called event-related synchronization (ERS) (Pfurtscheller & Lopes da Silva 1999). The ERD/ERS values are expressed as percentage and are within-subject measures of relative changes in the EEG (Pfurtscheller & Lopes da Silva 1999). As is the case with the EEG, also the ERD/ERS technique is characterized by a relatively good temporal resolution and provides a suitable method to assess dynamic brain oscillatory responses during cognitive processing.

Recently, interest on the effects of EMF emitted by MP on brain functioning has emerged. Several reports on adults, with somewhat conflicting results, exist on the effects of EMF emitted by mobile phones (MP) on the EEG (Croft et al. 2002, Eulitz et al. 1998, Freude et al. 1998, 2000, Huber et al. 2000, 2002, Krause et al. 2000b, 2000c, 2004, Röschke & Mann 1997): Both positive (Eulitz et al. 1998, Freude et al. 2000, Krause et al. 2000b, 2000c, 2004, Croft et al. 2002, Charalabos et al. 2006), and negative findings have been reported (Röschke & Mann 1997, Wagner et al. 1998, Hamblin et al. 2006, Oysu et al. 2005, Yuasa et al.

2006). The effects of EMF on cerebral blood flow have also been studied (Haarala et al. 2003, Huber et al. 2002), and as is the case with the EMF/EEG studies, the results from these studies are inconsistent.

Krause and co-workers have previously reported of EMF effects on EEG brain oscillatory activity during cognitive processing in adults (Krause et al. 2000b, 2000c, 2004). In the first year 2000 study (Krause et al. 2000b), during an auditory memory task, Krause et al. reported that the presence of EMF significantly increased the power of the 8–10 Hz EEG frequency band (Krause et al. 2000b) and modulated the EEG ERD/ERS (event-related desynchronization/synchronization) responses of the 4–6, 6–8, 8–10 and 10–12 Hz narrow frequency bands as a function of time and cognitive task. More specifically, in that study, the EMF effects were most obvious during memory recognition (as compared to encoding) such that in the 4–6 Hz EEG frequency band the presence of EMF decreased the initial ERS responses and increased these in the higher 6–8, 8–10 and 10–12 Hz EEG frequency bands. In the second year 2000 study (Krause et al. 2000c), Krause et al. reported that during a visual working memory task, the presence of EMF altered the ERD/ERS responses only in the 8–10 Hz EEG frequency range by increasing and delaying the ERD responses, however, varying also as a function of time and visual stimulus type (target vs. non-target). In the year 2004 replication study (Krause et al. 2004), Krause and co-workers replicated the first year 2000 study and observed some effects of EMF on the ERD/ERS responses in the 4–8 Hz EEG frequency range but noted that that “all eight of the significant changes in our earlier study were not significant in the present double blind replication” and that “EMF effects on the EEG . . . may be variable and not easily replicable for unknown reasons”. Such unsystematic observations indicate a need of further experimentation and the current study was conducted as one additional study on a continuum of our EMF-EEG-cognition studies. The specific aim of the present double-blind study was to assess possible MP effects on children’s event-related oscillatory EEG activity while these performed an auditory memory task (Krause et al. 1996, 2001). To our knowledge, this is the first report on the immediate effects of MP on children’s event-related EEG oscillatory activity during cognitive processing.

Methods

Participants

Data from 15 participants were gathered (6 boys and 9 girls age ranging from 10–14 years). All participants

were right-handed and native speakers of Finnish. The participants and their parents were given information about the nature of the study and a written consent from both the participant and at least one parent was also required. The experiment was conducted according to the ethical guidelines and procedures stated in the principles of professional ethics for psychologists in the Nordic countries.

Stimulus materials

The stimuli were 8 acoustically presented Finnish nouns spoken with a female voice. The mean duration of the stimuli was 520 ms and the stimulus words were presented in the beginning of audio files, the length of which were always 800 ms. The Neuroscan Stim (v. 3.0, NeuroScan, Compumedics USA, Texas, USA) system was used to control the presentation of the auditory stimuli. The stimuli were presented through E-A-RTONE ABR insert earphones (10 Ω) at a comfortable sound pressure level (~ 70 dB_{SPL}).

The experimental setting

The experimental design was modification of Sternberg's memory search paradigm (Krause et al. 1996). The memory set (encoding) consisted of four words. The probe (recognition) was always one word. The task was to decide whether the probe word was or was not presented in the memory set. In 50% of the trials, the probe word was among the memory set. The procedure and stimuli have been described in detail in a previous study (Krause et al. 2001).

Each of the memory sets was randomly drawn from a list of 8 Finnish nouns with the restriction that each word had to occur with equal frequency and only once in the same memory set. The stimuli were presented in two 30-min randomized blocks of 105 trials (MP off and MP on) of five words each (memory set: four words; probe: one word). The total registration time was about 60 min.

After calibration of the instruments the electrode cap was applied and the instructions were read aloud. After this, the participant was seated in a comfortable chair in a dimmed registration room and was instructed to look at a TV-screen placed 1.6 m in front of him/her and instructed to relax and avoid movement and eye-blinks.

EEG recording procedure

The EEG was recorded from 19 tin (Sn) electrodes using an Electrode-Cap (Electrop-Cap International Inc., Ohio, USA) according to the international 10/20 system of electrode placement. Small or medium-size caps were used depending on the participant's

head size. Two EOG-electrodes were placed on the outer canthi. The electrodes were referred to linked mastoids (right ear mastoid, left ear mastoid, middle of head ground). The data sampling rate was 250 Hz. Raw EEG signal was recorded using the Neuroscan 386 Scan 4.1 (NeuroScan, Compumedics USA, Texas, USA) data acquisition system with SynAmps amplifier (notch filter 50 Hz, low pass filter 50 Hz and high pass filter 0.10 Hz, NeuroScan, Compumedics USA, Texas, USA).

EMF procedure

Each EEG recording was subdivided into two 30-min segments, one with the MP turned off and the other with the MP turned on. The MP exposure order was counterbalanced across the participants, with the MP active in the first segment for half of the participants, and vice versa for the other half. A double-blind protocol was used, that is, the presence or absence of the EMF was unnoticeable for the participants under the investigation and the investigator was not informed about the order of the conditions. After the first segment, a short break was held and the participants filled a short form concerning subjective symptoms.

A standard GSM (Global System for Mobile Communication) phone was mounted to the participant's head over the left posterior temporal region, comparable to normal use, during both experimental conditions (MP off and on). In our previous studies the phone was detected to emit a weak buzzing noise during 'on' condition. To combat this problem, in the current study the phone's loudspeaker was removed, and the phone's battery was changed to a model that did not emit such a noise. No other modifications were done to the phone. The antenna was located about 20 mm from the head. 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 mean net forward power of the aerial was 0.25 W. The SAR (Specific Absorption Rate) values were hence measured with a SPEAG's Dosimetric Assessment System 3 (DASY3, Schmid and Partner Engineering AG, Zürich, Switzerland), and an adult generic twin phantom filled with brain tissue simulating liquid ($\sigma = 0.97$ ohm/m, $\epsilon_r = 40.7$). The SAR value averaged over 1 g of tissue was 1.40 W/Kg, and the measured peak value was 1.98 W/Kg. During the SAR measurement the same Electrode-Cap used in the actual experiment was attached on the phantom excluding the upper side so as not to prevent the movement of the sensor. The location of the measured peak value was on the upper cheek approximately 2 cm anterior and 2 cm inferior to the auditory canal.

The MP in the present study was identical to the one used in one of our previous studies with adults, however, in the current study the battery was replaced with a quieter one. An identical set-up was used in a recent behavioural study (Haarala et al. 2005). In the current study, in the end of each experimental session the subject was instructed to fill in a questionnaire in which the subjects were asked to estimate how sure they were that the phone was on/off on a 9-step Likert-scale (in which 1 = "I am absolutely sure that the mobile phone was on", 5 = "I have no idea about the status of the phone" and 9 = "I am absolutely sure that the mobile phone was off"). According to these reports, the subjects were not able to estimate the status of the phone any more accurately in the on condition than in the off condition which was tested with a paired-samples *t*-test: The mean estimate of the status of the mobile phone in the 'on' condition was 4.47 (SD = 1.85) and in the 'off' condition 4.47 (SD = 1.85) ($t(14) = 0.000$, $p = 1$).

The phone's experimental condition was controlled with a WinTesla service software (Nokia Research Center, Helsinki, Finland) running on a computer connected to the phone via a cable. After the appropriate experimental condition was set, the phone was disconnected from the cable, and mounted on the participant's head.

EEG data analyses

The digital EEG data were processed in a MATLAB 6.1 and 6.5 environments (The Mathworks, Massachusetts, USA). Time-frequency representations (TFR) 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. TFR of 1600 ms (−100 to 1500 ms from trigger) and 1–20 Hz were calculated for each participant, separately for both MP conditions for the no-stimulus 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. The calculations were performed for each EEG channel separately. Artefact rejection was set to $\pm 70 \mu\text{V}$. Poor quality signal channels (in which the EEG signal was visibly contaminated) were excluded from further analyses by means of visual inspections of the TFR displaying the absolute power values. These poor quality single electrodes were rejected from the original 19 electrodes.

After artefact rejection, the power in the reference interval TFR was averaged over time. Thereafter, the relative differences (event-related desynchronization and synchronization, ERD/ERS) in EEG power between the averaged reference interval and the actual stimuli (four stimuli during encoding and two

stimuli (positive and negative probe) during recognition) were calculated and expressed as percentage. This resulted in ERD/ERS TFR displaying the relative power differences between the reference interval and the actual stimuli as percentage as a function of frequency and time. Thereafter, the ERD/ERS TFR for each of the four stimuli in each memory set were averaged separately for each individual and for the two MP conditions. Also the TFR for the two stimuli during recognition were averaged similarly. After these calculations, four ERD/ERS TFR were obtained for each participant: encoding and recognition for both MP on and off conditions. The ERD/ERS data were then averaged over 5 electrode locations (Frontal FP1, FP2, F3, Fz, F4; Left Temporal F7, T3, C3, T5; Right Temporal F8, T6, C4; Central Cz, P3, Pz, P4; Occipital O1, O2. Channel T4 was excluded from analyses due to artefacts). These data were used in the statistical analyses.

The exposure orders for the 15 participants included in the final analyses were as follows: EMF off first 8 participants (53%, 4 girls, mean age 13.13 years, range 11–14 years) and EMF on first 7 participants (47%, 6 girls, mean age 13.14 years, range 10–14 years).

Statistical analyses

The nonparametric two-sided Quade test (Quade 1979), which compensates for dependencies between preceding and following points in the time-frequency space within one channel was used to assess the significance of the ERD/ERS responses separately for encoding and recognition separately for both MP conditions (MP off and MP on) with respect to the baseline. Thereafter, the statistical significance of the differences in the ERD/ERS TFR between the MP on and MP off conditions, separately for encoding and recognition was calculated using the same statistical test. The statistical computations were performed in the MATLAB 6.5 environment. The results from the Quade tests were displayed in probability TFR, in which statistically significant observations ($p < 0.05$) were shown as a function of EEG frequency and time. In order to minimize the type 1 error risk when conducting multiple statistical comparisons, we report and discuss only those results in the between groups probability matrices where the temporal duration of the statistically significant difference exceeds 100 ms.

Results

The mean ERD/ERS TFR for the five electrode locations for both memory encoding (upper part) and recognition (lower part) for both MP off and MP

on conditions as well as the results from all the statistical tests are displayed in Figure 1. In Figure 1, the ERD/ERS data are plotted using a time window from 0–1400 ms from stimulus onset separately for the five electrode locations (frontal, central, occipital, left temporal and right temporal). For each electrode

location, ERD/ERS values within both condition ('MP off' on left and 'MP on' on right side) are displayed in the middle row, while statistical significance of the ERD/ERS values within conditions are presented in upper row accordingly. The probability TFR presenting the statistically

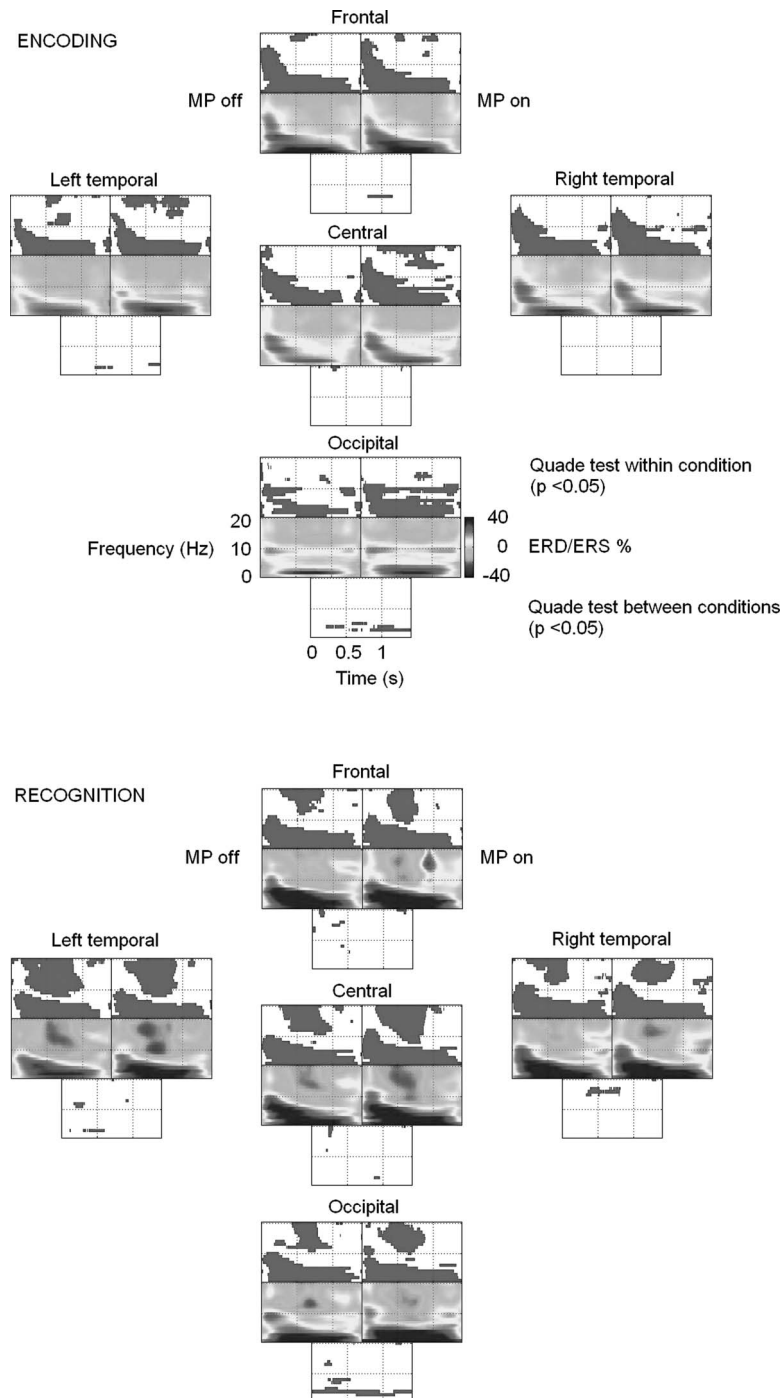


Figure 1. Mean ERD/ERS TFR and statistical probability TFR during encoding (upper part) and recognition (lower part) for the five electrode locations (frontal, central, occipital, left temporal and right temporal). In each TFR, the y-axis displays frequency (1–20 Hz) and the x-axis displays time (0–1400 ms after stimulus onset). In probability TFR, the values with $p < 0.05$ are marked with red. For each electrode location, ERD/ERS values within both condition ('MP off' on left and 'MP on' on right side) are displayed in the middle row, while statistical significance of the ERD/ERS values within conditions are presented in upper row accordingly. The probability TFR presenting the statistically significant differences between conditions are displayed in the lowest row.

significant differences between conditions are displayed in the lowest row.

As expected (Krause et al. 1996) encoding (upper part) and recognition (lower part) evoked distinct ERD/ERS responses also in the present study on children (Krause et al. 2001) (Figure 1). As can be seen in Figure 1, the encoding of the auditory stimuli elicited statistically significant ERS in the $\sim 1-8$ Hz frequencies ($\sim 100-1300$ ms) and in the $\sim 1-15$ Hz frequencies ($\sim 0-400$ ms). Recognition, on the other hand, elicited statistically significant ERS in the $\sim 1-8$ Hz frequencies ($\sim 100-1300$ ms) and ERD in the $\sim 10-20$ Hz frequencies ($\sim 300-1400$ ms).

During encoding (Figure 1, upper part), there were statistically significant ($p < 0.05$) differences between the ERD/ERS responses between the two MP conditions (off and on) in the $\sim 4-8$ Hz frequencies ($\sim 200-1400$ ms) in the frontal, occipital and left temporal electrodes. During recognition, there were statistically significant ($p < 0.05$) differences between the ERD/ERS responses between the two MP conditions (off and on) in the $\sim 4-8$ Hz frequencies ($\sim 0-1400$ ms) in the occipital and left temporal electrodes. In addition, during recognition, statistically significant differences between the ERD/ERS responses between the two MP conditions (off and on) were observed in the ~ 15 Hz frequencies ($\sim 400-800$ ms) in the right temporal electrodes.

Discussion

The aim of the present double-blind study was to assess possible MP effects on children's event-related oscillatory EEG activity during an auditory memory task (Krause et al. 1996). To our knowledge, this is the first report on the immediate effects of MP on children's event-related EEG oscillatory activity during cognitive processing.

As anticipated on the basis of previous research, auditory encoding and recognition elicited dissimilar ERD/ERS responses also in children (Krause et al. 1996, 2001). A novel basic finding in the current study was the observation that auditory recognition elicited a higher frequency ($\sim 10-20$ Hz) ERD phenomenon, which has only recently been reported in adult and elderly subjects (Karrasch et al. 2004). The role of such higher frequency oscillations in cognitive processing is under investigation (Pesonen et al. 2006).

In the current study, we witnessed effects of the active MP on the ERD/ERS responses both during encoding and recognition in the $\sim 4-8$ Hz and ~ 15 Hz EEG frequencies. During *encoding*, the active MP increased the ERS responses in the $\sim 4-8$ Hz EEG frequencies and broadened the responsive frequency band in the frontal, occipital

and left temporal electrode locations. Additionally, during encoding, slightly greater ERD values were witnessed while the MP was on as compared to the MP off condition in the ~ 8 Hz frequency band, however, only in the frontal electrodes. During *recognition*, the active MP increased the ERS responses and broadened the responsive frequency band in the occipital and left temporal electrodes in the $\sim 4-8$ Hz frequency range. Additionally, during recognition, the active MP increased the ERD responses in the right temporal electrodes in the ~ 15 Hz frequency range. These effects of MP observed in the current study in children were of $\sim 5-10\%$ in magnitude, thus being of the same extent as in previous reports on adults (Krause et al. 2000b, 2000c, 2004).

Our current observations are in congruence with the EMF EEG studies by Krause and co-workers (Krause et al. 2000b, 2000c, 2004) in which modest effects of EMF on the ~ 8 Hz EEG responses were reported. It may be the case that EMF influences brain oscillatory responses in the alpha frequency range (around 8 Hz) both in adults and in children. One should note, however, that the EMF effects on the ERD/ERS responses (increase vs. decrease) are not systematic between the studies and the reason for such inconsistencies remains unclear.

In the current study, the mobile phone was attached to the left side of the subjects' heads and the effects of the EMF on the ~ 8 Hz ERD/ERS responses were somewhat lateralized to the left temporal electrodes. In our recent replication study on an adult population (Krause et al. 2004), in which the mobile phone was attached to the left side of the head, similar left lateralized EMF effects were reported as observed in the current study. However, to which extent the observed MP effects on the ERD/ERS responses are dependent on the side of the MP phone remains unclear, and cannot yet be answered by means of the results from these few studies.

The EEG signal analysis technique utilized in the current study (wavelet transformation) allowed us to study the reactivity of several EEG frequency bands simultaneously. As a result of this, as a novel finding, we witnessed that the presence of EMF broadened the responsive synchronizing frequency band around 8 Hz both during encoding and recognition. It has not been possible to assess such effects in our previous EMF EEG studies, in which the responses of narrow EEG frequency bands have been analysed separately. Although the wavelet signal-analysis method is characterized by several positive features, this technique results in both temporal (lower frequencies) and frequency (higher frequencies) blurring. As a result of this, possible temporal effects of EMF on the ERD/ERS responses in the lower EEG frequencies can be studied only on a ~ 100 ms

scale. The ERD/ERS responses during cognitive processing are typically relatively slow (Krause et al. 1996, Pesonen et al. 2006) (several hundred milliseconds) and thus this temporal blurring of the signal does not influence the results.

It should be noted that no physiological mechanisms mediating MP effects on the ERD/ERS responses have yet been identified. One possibility could be mild cortical temperature changes which might affect synaptic transmission (Preece et al. 1999). However, not all studies (Van Leeuwen et al. 1999) agree on that EMF emitted by MP would have effects on cortical temperature.

The present results do not allow any conclusions concerning the possible effects of long-term cellular phone use on cognition or health. These questions are to be answered by future studies. Currently, the physiological mechanism underlying the EMF effects on brain oscillatory responses remains unclear.

Conclusions

EMF emitted by active MPs has effects on children's brain oscillatory responses in the ~ 4 –8 Hz and ~ 15 Hz EEG frequencies during cognitive processing.

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