

MOBILE phones emit a pulsed high-frequency electromagnetic field (PEMF) which may penetrate the scalp and the skull. Increasingly, there is an interest in the interaction of this pulsed microwave radiation with the human brain. Our investigations show that these electromagnetic fields alter distinct aspects of the brain's electrical response to acoustic stimuli. More precisely, our results demonstrate that aspects of the induced but not the evoked brain activity during PEMF exposure can be different from those not influenced by PEMF radiation. This effect appears in higher frequency bands when subjects process task-relevant target stimuli but was not present for irrelevant standard stimuli. As the induced brain activity in higher frequency bands has been proposed to be a correlate of coherent high-frequency neuronal activity, PEMF exposure may provide means to systematically alter the pattern fluctuations in neural mass activity. *NeuroReport* 9: 3229–3232 © 1998 Lippincott Williams & Wilkins.

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Mobile phones modulate response patterns of human brain activity

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Introduction

Cellular mobile phones emit pulsed high-frequency electromagnetic fields (PEMF). The possible interactions of GSM (Global System for Mobile Communication) microwaves and human organs, in particular the brain, has been broadly discussed. A considerable body of literature exists that examines the influence of electromagnetic fields on brain and behavior.^{1–4} The complexity of research in this field, as well as the lack of well controlled investigations concerning the influence of electromagnetic fields on behavior, make it a field full of speculation. There is as yet a lack of theoretical framework which would allow the systematic tracking of suspected phenomena.

Low-frequency electromagnetic activity is effectively screened by biological tissue. Twenty years ago Adey and his associates¹ discussed the possibility that high-frequency electromagnetic radiation would penetrate scalp and skull and thus reach neurons. These authors further postulated that radiation would alter aspects of membrane function if modulated with lower frequencies. Cellular phones emit such modulated high-frequency radiation. The goal of this investigation was to determine empirically whether radiation generated by cellular phones might affect neural responses.

One possible way of investigating neural mass

activation is to study changes in the human electroencephalogram (EEG). So far attempts have failed to show an influence of PEMF on the spontaneous awake EEG.⁵ However, under more demanding experimental conditions, Freude *et al.*⁶ demonstrated effects of PEMF on slow brain potentials. They described differential effects for a low demanding (simple self-paced finger movements) and a high demanding (visual monitoring task) condition with and without PEMF exposure. A reduced slow brain potential amplitude was found only in the high demanding condition during PEMF exposure. The present study investigated a different set of cognitive tasks for influences of PEMF on EEG and used methods of signal analysis that extract oscillatory neural responses from the EEG. Based on the analysis in the frequency-domain, this approach ensures that brain signals that are time- but not phase-locked to the stimulus are preserved after averaging across repeated stimulus presentation. This procedure reveals aspects of brain activity that are not visible with conventional averaging. The outcome of frequency-domain analyses is called induced brain activity. It has been proposed that the induced brain activity in higher frequency bands may be a correlate of coherent high-frequency neuronal activity which is discussed as a physiological indicator of perceptual and higher cognitive processes (for review see Refs 7,8).

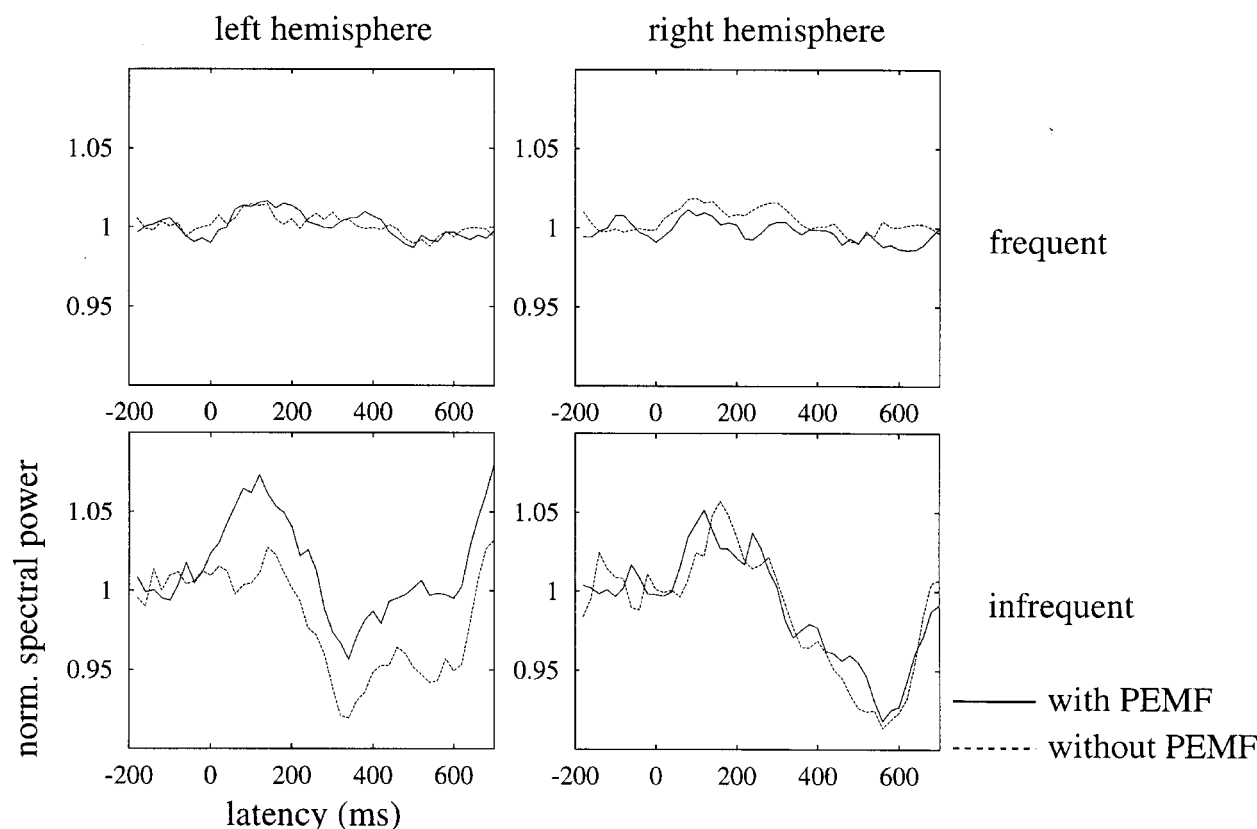


FIG. 1. Changes of the event-related spectral time course of the EEG in the frequency band from 18.75 to 31.25 Hz after the presentation (at 0 ms) of frequent (upper row) and infrequent task relevant tones (lower row). The frequent 1000 Hz tones were presented with a mean interstimulus interval of 2 s. The infrequent 2000 Hz tones were delivered in 10% of the trials and subjects were asked to respond with a button press to these targets using their right hand. Another 10% of the stimuli were task-irrelevant varying complex novel sounds (not shown in the figure). The figure demonstrates the averaged normalized spectral power across all channels over the left (left panel) and the right hemisphere (right panel) grand averaged across 13 subjects separately for the different experimental conditions. The solid line codes the condition with exposure to PEMF, the dashed line the condition without PEMF exposure.

Materials and Methods

We recorded EEG during an auditory discrimination task (oddball paradigm), with or without exposure to PEMF. In this task, a series of 1000 Hz tones was presented with an interstimulus interval of 2 s. Ten percent of the stimuli were 2000 Hz tones and the subject was asked to respond with a button press to these targets. In another 10% of the trials, the 1000 Hz standard tones were replaced by varying complex novel sounds which were task-irrelevant. Thirteen healthy male subjects aged 21–27 years gave written consent to participate in the study. EEG (SynAmps) was recorded from 30 positions on the scalp (FP1, FP2, F3, F4, C3, C4, Cz, Oz, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Pz, FT9, FT10, FC5, FC6, CP1, CP2, CP5, CP6, A1, A2; see also Fig. 2) and amplified in the frequency range from DC to 30 Hz. Horizontal and vertical eye movements were also monitored.

Four blocks of 450 stimuli were presented according to a balanced experimental plan under single-

blind conditions. During two of the blocks the telephone aerial emitted a 916.2 MHz electromagnetic field pulsed with a frequency of 217 Hz a pulse width of 577 μ s (a characteristic that corresponds to the European digital net). The radiated peak power of the aerial was 2.8 W, the GSM standard signal was provided without acoustic signal transmission and without power management. The mobile phone was mounted to the subject's head such that the base of the antenna was positioned over the left posterior temporal region (above T3) with the transmitter being operated from a separate room. Care was taken that no secondary phenomena (e.g. acoustic noise) would indicate to subjects whether the transmitter was switched on or off.

Averaged waveforms were calculated for each stimulus class across epochs of 1000 ms, including a 240 ms pre-stimulus baseline. Artifact-contaminated epochs with a signal deviation of $> 75 \mu$ V in the EEG or 100μ V in the EOG were excluded. These waveforms were used for the analysis of components of the evoked potentials as well as for a spectral analysis

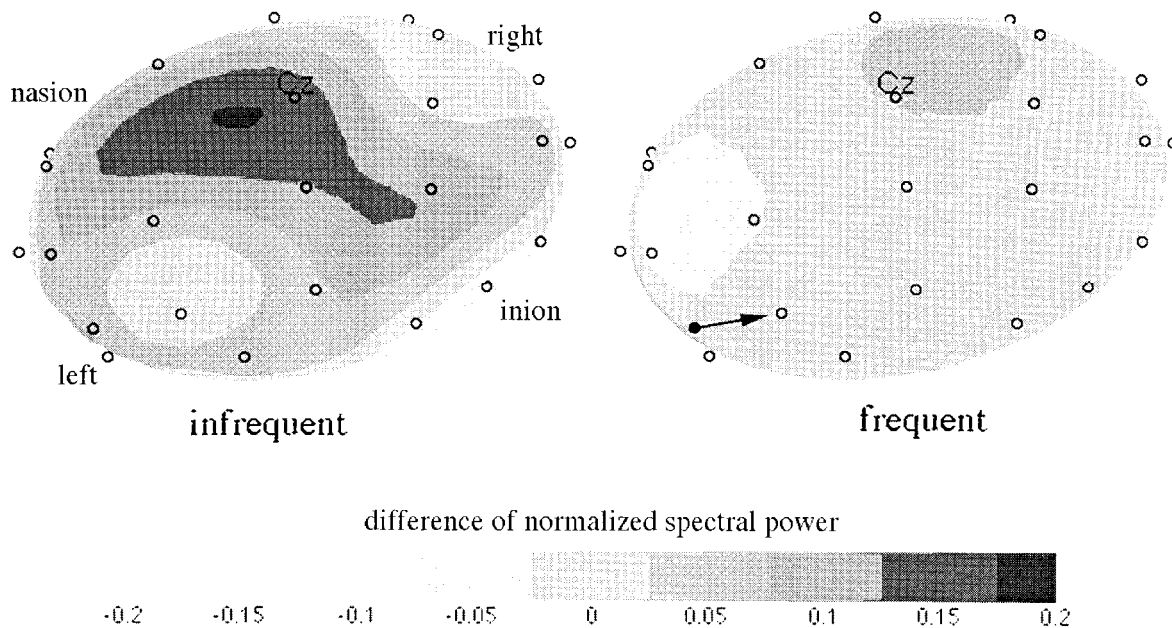


FIG. 2. Topography of the difference of the averaged normalized spectral power between the conditions with and without PEMF exposure in the analyzed frequency band for the latency range 260–380 ms after stimulus onset is shown for the task-relevant infrequent (left panel) and the frequent condition (right panel). As the spectral power is below the mean baseline level in this latency range, the darker gray means a smaller reduction with than without PEMF exposure. Note that the largest difference is seen between Cz and C3, i.e. over brain areas involved in motor preparation. Black circles indicate the mean electrode positions. The base of the antenna was positioned above the T3 electrode position (filled circle in the right panel) and pointed into the direction of CP5 as indicated by the arrow. Measurements of the specific absorption rate of radiation in an anatomically full-scaled head phantom revealed that the power of radiation was largest near the base of the antenna.

of the averaged waveforms. For frequency-domain analyses (see also Ref. 9), a method similar to the event-related perturbation analyses was applied using the *avg_q* software.¹⁰ In the artifact-free raw data (same rejection criteria as reported above), power spectral estimates were derived from Fourier transforms on time-segments 120 ms in length shifted over the epoch of measured data in steps of 20 ms starting 240 ms before stimulus onset until 760 ms after stimulus onset. The spectral power estimates from single epochs were selectively averaged for each segment around stimulus onset and stimulus class. The mean power spectra were transformed with respect to baseline-related changes in two different ways. First, normalized mean power spectra were calculated by dividing each single mean spectral power within one frequency bin by the mean spectral power across all corresponding baseline segments. Second, the portion of single trial spectral power estimates below or above the mean single trial baseline spectral power (relative gain) was computed. This parameter was obtained by comparing the spectral power for a window position with the respective baseline values separately for all experimental conditions and time/frequency bins. This relative gain is insensitive to occasional deviant spectral power estimates and was used to

verify differences occurring in normalized spectral power.

Statistical evaluation was carried out for the spectral power changes in the time window of P300 occurrence (from 260 to 380 ms) using a three-factor repeated measures ANOVA. The repeated measures factors were PEMF (with *vs* without), hemisphere (left *vs* right) and the intrahemispheric electrode position (13 locations without the central positions).

Results

Analysis of the averaged EEG responses to the stimuli did not indicate any dependency on the status of the transmitter. If PEMF altered neural functioning, it might be detectable in the pattern of the induced brain activity. As demonstrated in Fig. 1 for the averaged normalized spectral power across 13 subjects, a modulating effect of PEMF was seen for the target condition in the frequency band 18.75–31.25 Hz. No such effect was found for the stimuli that were not task-relevant (standard or novel).

When present, PEMF modulated mainly the hemisphere directly exposed to the electromagnetic radiation and only in combination with task-relevant

stimuli (PEMF by hemisphere interaction: $F(1,12) = 9.86$; $p < 0.009$ for the spectral power changes of the 18.75–31.25 Hz band in the P300 time window from 260 to 380 ms). The topography of this effect is illustrated in Fig. 2, which shows the difference of the normalized spectral power between the conditions with and without PEMF exposure averaged across all subjects. The largest difference is seen approximately between Cz and C3. This result was robust with respect to the choice of the particular type of analysis and also appeared for the relative gain. The corresponding PEMF by hemisphere interaction was $F(1/12) = 13.54$ ($p < 0.004$).

To further verify that the described differences reflect a modulation of the induced brain activity, the averaged waveforms were used for a short term spectral analysis with the same characteristics as for the frequency-domain analysis. As for the averaged EEG responses, the spectral power of the averaged waveforms did not indicate any dependency on the status of the transmitter for any of the time/frequency bins or experimental conditions.

Discussion and Conclusion

The study demonstrated that PEMF may alter distinct aspects of the brain electrical response to acoustic stimuli in an oddball paradigm. More precisely, results demonstrate that the induced, but not the evoked, brain activity during PEMF exposure can be different from that not influenced by PEMF radiation. The effect appeared when subjects processed task-relevant target stimuli but was not present for irrelevant standard or novel stimuli. When present, PEMF modulated mainly the induced brain activity in the hemisphere directly exposed to the electromagnetic radiation and only in the high-frequency band. The specificity of the effect excludes the possibility that it was caused by technical artifacts.

This gives further evidence to the possibility that neural responses as reflected in the EEG can be

modulated through radiation emitted by mobile phones. Whereas the spontaneous awake EEG seems to be unaffected by PEMF,⁵ the present results as well as the results of Freude and co-workers⁶ show that effects of PEMF on the event-related brain activity appear when stimuli are behaviorally relevant.

We conclude from the present results that PEMF may cause perturbations in the event-related spectral time course, i.e. that neural oscillations which are reflected by the induced brain activity are altered in response to task-relevant stimuli. This study does not allow us to determine any health risk nor is it clear what behavioral consequences PEMF exposure might have. Since oscillatory brain responses have been related to object recognition,^{7–9} PEMF exposure may provide a means to systematically alter the pattern fluctuations in neural mass activity and therefore be used to further study the functional meaning of oscillations in neural networks. It might even be conjectured that brain functions could be modified by PEMF in a manner so delicate that it has not been recognized in the course studies performed so far regarding the possible influence of the use of mobile phones on brain functions.

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