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The Effects of Mobile-Phone Electromagnetic Fields on Brain Electrical Activity: A Critical Analysis of the Literature

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We analyzed the reports in which human brain electrical activity was compared between the presence and absence of radio-frequency and low-frequency electromagnetic fields (EMFs) from mobile phones, or between pre- and post-exposure to the EMFs. Of 55 reports, 37 claimed and 18 denied an Emf-induced effect on either the baseline electroencephalogram (EEG), or on cognitive processing of visual or auditory stimuli as reflected in changes in event-related potentials. The positive reports did not adequately consider the family-wise error rate, the presence of spike artifacts in the EEG, or the confounding role of the two different EMFs. The negative reports contained neither positive controls nor power analyses. Almost all reports were based on the incorrect assumption that the brain was in equilibrium with its surroundings. Overall, the doubt regarding the existence of reproducible mobile-phone EMFs on brain activity created by the reports appeared to legitimate the knowledge claims of the mobile-phone industry. However, it funded, partly or wholly, at least 87% of the reports. From an analysis of their cognitive framework, the common use of disclaimers, the absence of information concerning conflicts of interest, and the industry's donations to the principal EMF journal, we inferred that the doubt was manufactured by the industry. The crucial scientific question of the pathophysiology of mobile-phone EMFs as reflected in measurements of brain electrical activity remains unanswered, and essentially unaddressed.

Introduction

The seminal question regarding the pathophysiology of the radio-frequency and low-frequency electromagnetic fields (EMFs) produced by mobile phones is whether one or both of the fields cause or contribute to the onset of disease. Both EMFs enter the user's brain during normal phone use; consequently, their effects on brain metabolism have been studied intensively. Our purpose was to review the reports in which the measured endpoints directly involved brain electrical activity, and to assess whether the reports provided credible scientific evidence of a cause-effect relationship.

In the next section, we describe how the pertinent reports were identified, give reasons for our treatment of the independent variable, and briefly describe the main

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methods for characterizing brain electrical activity. In many reports the mobile-phone EMFs were discussed in relation to the concept of dose; however, the reports were readily comprehensible without the need to discuss that cluster of arguments.

In Section 3, we inquire critically into the reports that concluded mobile-phone EMFs had affected human brain electrical activity, either *during* or *after* EMF exposure. Even though 67% of the reports were self reported as positive, significant doubt remained whether mobile-phone EMFs affected brain electrical activity.

In the last section, we analyze the studies globally and explain the basis of our view that the doubt was manufactured by the mobile-phone industry.

Methods

Databases

We searched electronic databases (PubMed, Science Citation Index) using combinations of an electrical term (i.e., field, electromagnetic, electric, magnetic), a device (i.e., mobile phone, cellular phone), and an outcome (i.e., electroencephalogram, event-related potentials, evoked potentials, brain electrical activity) to identify English-language reports that involved the effects of mobile-phone EMFs on the brain electrical activity of human subjects. The inclusion criteria were: (1) a reasonable description of the experimental conditions; (2) use of a control group; (3) blinding of the experimental subjects to the treatment; (4) statistical evaluation of the data. The exclusion criteria were: (1) the use of thermal EMFs; (2) experiments where the measured endpoints did not include at least one electrophysiological dependent variable; (3) experiments that did not include EMF frequencies in the radio-frequency range associated with mobile-phone technology. All other factors including blinding of the investigators, counter-balancing of experimental conditions, performance of sham studies, inclusion of positive controls, corrections for multiple comparisons, the role of artifacts, and the reasonableness of the experimental design were considered with regard to the weight given to the report rather than to its admissibility as evidence of the ability of the EMFs to affect brain activity. Reports limited to low-frequency EMFs were reviewed elsewhere (Carrubba and Marino, 2008).

The Independent Variable

GSM technology, the present standard in the mobile-phone industry, results in the production of two distinct EMFs. The radio-frequency GSM EMF is a high-frequency (1–2 GHz) pulse lasting 577 μs, transmitted every 4,615 μs (217-Hz burst rate) at 1–2 watts, delivered from an antenna located near the head (Garg and Wilkes, 1998). The low-frequency GSM EMF is a 217 Hz magnetic field, about 300 mG more or less, produced by the battery current that facilitates the bursting behavior (not by the antenna) (Linde and Mild, 1997; Pederson, 1997; Perentos et al., 2006).

Information in the reports regarding both EMFs was generally sketchy, but its absence was not a serious problem. Knowing that the subjects were exposed to actual or simulated GSM EMFs was sufficient because our focus was on the causal association of GSM EMFs and the occurrence of changes in brain electrical activity. Many investigators provided calculations and measurements of the specific absorption rate and/or engineering details of specific mobile phones. We did not list the information because the investigators did not deterministically relate it (empirically or theoretically) to the effects they claimed.

Dependent Variables

Brain electrical activity was represented as voltage time series measured from standardized locations (10–20 system) using metallic electrodes glued to the scalp (electroencephalogram (EEG)). In most experiments, the EEG was recorded in the absence of a specific sensory stimulus (baseline EEG) and compared between the presence and absence of the EMF, or between pre- and post-exposure (Figure 1). Spectral analysis was the common method for characterizing the baseline EEG; the signals were decomposed by Fourier analysis into their component frequencies, each represented by a coefficient (called power and expressed in units of μV^2). The spectral frequencies were band-limited, sampled, subdivided, combined, and normalized in numerous ways; it was unnecessary to list the details (which were rarely the same in different studies). The alpha band (8–12 Hz) was the focus in many studies.

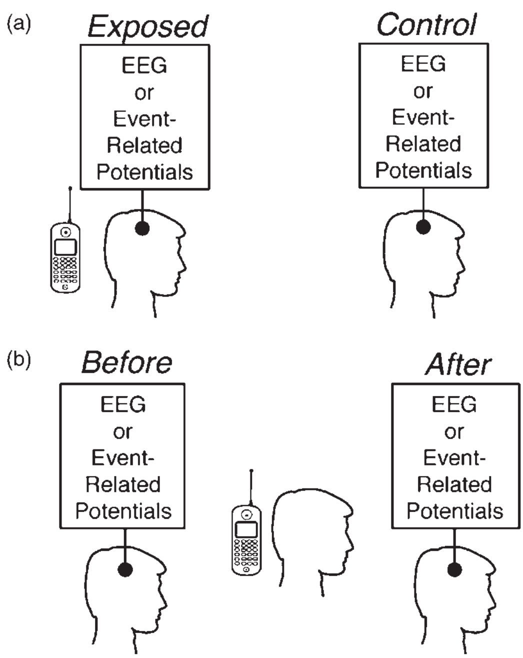

Figure 1. Experimental procedures used to study the effect of mobile-phone electromagnetic fields on brain electrical activity. (a) The electroencephalogram (EEG) was recorded in the presence and absence of mobile-phone EMFs. In experiments where actual mobile phones were used, the EMFs consisted of radio-frequency fields produced by the antenna, and low-frequency magnetic fields produced by the battery current. In the reports where simulated mobile-phone EMFs were applied, the subjects were exposed to only radio-frequency EMFs. Brain electrical activity was characterized by measuring either baseline EEG or event-related potentials superimposed on the baseline EEG as a result of cognitive processing of visual or auditory stimuli. (b) Brain electrical activity was recorded before and after exposure to mobile-phone EMFs, but not during exposure.

In other experiments, brain electrical activity was studied while the subject was responding to a specific stimulus by exhibiting an event-related potential (a change in the EEG due to specific sensory or cognitive stimuli; Lopes da Silva, 1999). Presentation of a sensory stimulus as a relatively rare event (for example, 500-Hz tones among more common 1,000-Hz tones) was a typical technique for studying cognitive processing (oddball paradigm). When a stimulus was presented in the absence of any expected cognitive or behavioral response, we referred to the event-related potential as an evoked potential (Lopes da Silva, 1999). As in the baseline EEG studies, event-related potentials were compared between presence and absence of the EMF or between pre- and post-exposure. The amplitudes of their various components and the corresponding latencies (from the time of application of the stimulus) were determined by time averaging the EEG over repeated applications of the stimulus, resulting in 3–6 variables, depending on the study.

Several more unusual variables were also measured including slow potentials, desynchronization reactions, EEG correlation, and magnetic (as opposed to electric) fields. Details of these methods are given elsewhere (Lopes da Silva, 1999).

GSM EMFs and Brain Electrical Activity

Effects During Exposure

The influence of EMFs from a mobile phone on the resting EEG was examined in 36 subjects exposed for 15 min, and an increase in relative alpha power during and after field exposure was described (Reiser et al., 1995). However, multiple tests were performed (16 electrodes, 6 frequency bands, 2 experimental conditions, and 3 exposure durations were evaluated) with no corrections for family-wise error. Another limitation involved the interaction of the EMFs with the scalp electrodes. The low-frequency modulation of the radio-frequency field and the low-frequency modulation of the battery current *both* probably produced spike artifacts at the input of the EEG amplifier (Carrubba et al., 2007a); the potential role of these artifacts was not adequately addressed (see below).

In an experiment involving the effect of mobile-phone EMFs (900 MHz, 217 Hz modulation, 50 $\mu W/cm^2$) on the EEG (recorded from C_3 and C_4) in 34 subjects, no effect on spectral power was found during a 3.5-min exposure (Röschke and Mann, 1997). Positive controls were not included; consequently, the sensitivity of the experiment for detecting an effect remained unaddressed.

Hietanen et al. (2000) studied the effect of 5 different mobile-phone EMFs on the EEG from 21 derivations in 19 subjects. Ninety *t* tests were performed (4 brain regions × 4 frequency bands × 5 phones) and only one significant difference from the control EEGs was found, clearly supporting the investigators' conclusion that there was no evidence of an effect of the mobile-phone EMFs on the EEG.

Croft et al. (2002) measured baseline EEG and auditory evoked potentials from 24 subjects in the presence and absence of a mobile-phone EMF, and analyzed the data in terms of numerous dependent variables. As was usually the case when many statistical tests were performed, a few were pair-wise significant; they included a decrease at 1–4 Hz and an increase at 8–12 Hz in the resting EEG, and altered sound-induced decrements at 4–8 Hz, 12–30 Hz, and 30–45-Hz in the evoked-potential measurements. The investigators concluded that mobile phone EMFs affected neural function, but a more parsimonious explanation was that the few significant effects they observed occurred by chance.

D'Costa et al. (2003) compared the EEG in the presence and absence of a mobile-phone EMF. The data was obtained during a series of 5-min on/off cycles and analyzed using contralateral electrode derivations as respective references (for example, O_1 derivation referenced to O_2). In 12 tests (3 data sets $\times$ 4 frequency bands), 3 effects (one in alpha and two in beta) were found. Considered as a prospective study, the investigators' conclusion ("the results of this study lend support to EEG effects of mobile phones") seems warranted because the family-wise error rate (P_{FW}) for 3 tests at a pair-wise level of $p < 0.05$ is $P_{FW} < 0.02$. This interpretation was strengthened by their results from a sham analysis (phone in the standby mode) in which 0/12 tests were significant. The investigators did not explain the reason for their choice of electrode configuration, which corresponded to the hypothesis that mobile-phone EMFs affected brain electrode activity more at one location than another (or not), rather than their professed hypothesis, which was that they affected brain electrical activity (or not). A limitation in the study was the unaddressed problem of electrode artifacts, which are EMF-electrode interactions that have no physiological significance.

In another experiment involving a typical mobile-phone EMF (902 MHz, burst frequency 217 Hz, maximum power 2 W, average power 0.25 W), Curcio et al. (2005) described increased spectral power at 9 and 10 Hz during exposure (and a weaker after-effect). However, the conclusion was based on five 3-way ANOVAs, only one of which was statistically significant. Moreover, the effect was small and the variance was large. For example, at 9 Hz the EEG power while the field was present was (mean $\pm$ SD) 0.8 ± 0.3, compared with 0.7 ± 0.4 for the control; the result at 10 Hz was similarly problematical.

Croft et al. (2008) repeated the study (Curcio et al., 2005) using many more subjects and found increased alpha power during EMF exposure, using one-tailed tests. A major shortcoming in the study was the presence of audio noise from the phone circuitry. The investigators reported that 2 subjects had been unable to hear the sound; however, whether it could be discerned by any of the other 107 subjects was not evaluated.

Kleinlogel et al. (2008a, 2008b) found no effect of mobile-phone EMFs on brain electrical activity, but the studies had too many independent variables (three different mobile phones), too many dependent variables (baseline EEG visual evoked potentials and auditory evoked potentials), and too few subjects ($N = 15$) to have any reasonable chance of avoiding a type II statistical error.

A German group investigated the effects of mobile-phone EMFs on brain electrical activity during sleep (Mann and Röschke, 1996; Wagner et al., 1998, 2000). In the first study (Mann and Röschke, 1996), the EEG from one derivation was analyzed in 12 subjects on successive nights during the presence (8 h) and absence of a mobile-phone EMF. Spectral power during REM sleep was increased 5% during EMF exposure but not in the other sleep stages. A finding of 1 pair-wise significant result in 5 tests (5 sleep stages considered) corresponds to a family-wise error rate of 0.23, thus the study provides no reliable evidence that EMFs affected the EEG. In a second (Wagner et al., 1998) and third (Wagner et al., 2000) study (24 and 20 subjects, respectively), the investigators reported failure to demonstrate an effect of mobile-phone EMFs on the EEG.

A Swiss group continuously recorded the EEG of 24 subjects during an 8-h night-time sleep session while the subjects were intermittently (15 min on/15 min off) exposed to mobile-phone EMFs (Borbély et al., 1999; Huber et al., 2003); the subjects were sham-exposed one week earlier or later. Power spectra were computed and compared in frequency bins of 0.25 Hz in the range 0–25 Hz (100 statistical tests), and the results were presented in two publications. When the investigators focused on the time between sleep onset and the first episode of REM sleep, they found many pair-wise significant comparisons in alpha (Figure 2a; Borbély et al., 1999). When the chosen EEG analysis interval was the first 30 min after lights off (the period during which the subjects were falling asleep) (Huber et al., 2003), there were far fewer pair-wise significant comparisons (Figure 2b). The major limitation regarding the investigators' conclusion that they had demonstrated an EMF effect on the EEG was that they presented results for only two time intervals. The investigators disclosed neither the number of intervals analyzed nor the reason the data was not

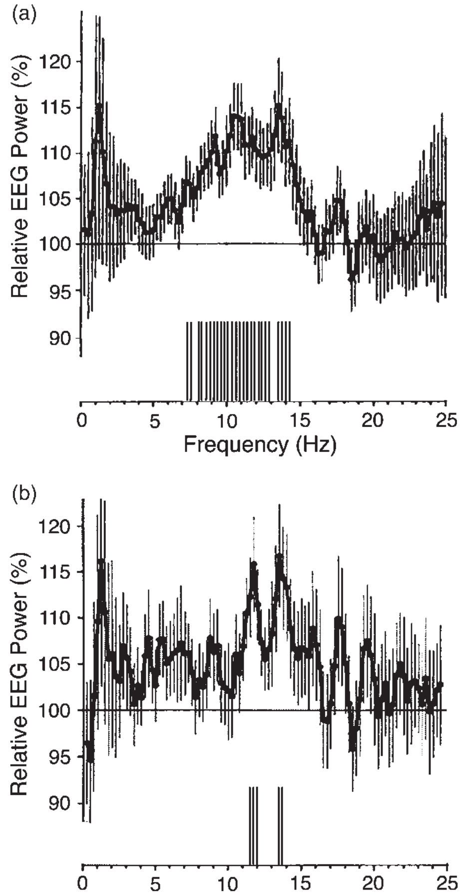

Figure 2. The role of the analysis interval in the decision regarding whether mobile-phone EMFs affected brain spectral power. (a) EEG data analyzed for the period between sleep onset and initial REM episode. (b) Same data analyzed for the first 30 min period after lights off. The ordinate values are the means (± SE) of the spectral power relative to the control (taken as 100%). The bars indicate the frequencies for which the statistical comparison was pair-wise significant at $p < 0.05$. Data in (a) and (b) from Borbély et al. (1999) and Huber et al. (2003), respectively.

divided according to sleep stages, which is normally how effects on sleep are studied. As was common in the reports we reviewed, the investigators extensively discussed the specific absorption rate but failed to relate the discussion to their results. They also did not discuss the potential artifacts due to electrode pick-up.

Fritzer et al. (2007) investigated whether night-long EMF exposure affected the spectral power in ten subjects using a separate control group, but found no field-induced changes in power at any frequency in either REM or non REM sleep. The failure to use the exposed subjects as their own controls was a serious error.

Lebedeva et al. (2000) recorded the EEG from 16 derivations in 24 subjects, and reported that the average fractal correlation dimension increased during and after exposure to a mobile-phone EMF. Similar results were found when the EMF was applied to subjects during sleep (Lebedeva et al., 2001). The studies were rare examples of an experimental design that considered the possibilities that (1) the stimulus-response relationship might be nonlinear, and (2) the subjects might respond differently from one another. The difficulty with both studies was that fractal analysis of biological time series data is inherently problematical because the mathematical techniques presume noise-free stationary data, which is far from the case for the EEG. The validity of the fractal analysis of the EEG must be established using surrogate analysis (Theiler et al., 1992) or some other control procedure, which the investigators did not do.

Estonian investigators published five reports dealing with the effect of exposure to pulse-modulated 450-MHz fields on brain electrical activity (Bachmann et al., 2005; Hinrikus et al., 2007, 2008a, 2008b, 2004). Initially, they examined the relative spectral power in the EEG from 23 subjects who each received 10 cycles of 1-min exposure followed by a 1-min control period (Hinrikus et al., 2004). On average, there were no effects on baseline EEG; however, there were also no effects when the subjects were exposed to light, indicating that the experiment was woefully insensitive. The investigators claimed to have observed EMF effects on theta frequencies when the data was evaluated separately in each subject. However, the post-hoc analysis was unprotected against an explanation based on chance. In a subsequent similar study involving 13 subjects (but no positive control) increased relative power (about 6%) due to EMFs was reported (Hinrikus et al., 2008b), but in the context of numerous 3-way ANOVAs, the great majority of which were statistically insignificant.

In two other studies, a novel form of nonlinear analysis of the EEG time series was employed, and 10 of 38 subjects were shown to have responded to the EMF by exhibiting altered brain electrical activity (Bachmann et al., 2005; Hinrikus et al., 2007). Unlike multifractal analysis to which the method has some similarities, the investigators' method did not attempt to characterize the source (the brain of the subject); the validity of the method therefore did not depend on the stationarity of the data. The major limitation was that only 10 exposed and control epochs were used in the statistical comparisons for each subject, possibly accounting for the low response rate (10/38). The possible influence of spike artifacts was not considered.

The investigators reanalyzed the EEGs obtained in their four studies (4 males were deleted from their 2005 study) to evaluate the effect of mobile-phone EMFs using a linear method (spectral power), but without averaging across subjects (Hinrikus et al., 2008a); for unexplained reasons only the parietal derivations were considered. They found 13–31% of the subjects detected the field, depending on the modulation frequency. The investigators did not explain why they used a linear method after having achieved some success using a nonlinear approach.

A French group investigated the effects of GSM EMFs on auditory evoked responses from normal and epileptic subjects; the EEG was recorded from 32 electrodes in the presence and absence of the fields and analyzed three different ways in separate publications (Maby et al., 2004, 2005, 2006). First, spectral correlation coefficients, latency, and amplitude of the time-averaged signals were computed from 14 of the electrodes. The reported field-induced effects, averaged over the subjects, were decreased N100 amplitude and spectral correlation coefficients for both groups, a reduction in N100 latency in the normal subjects but an increase in the epileptics, and increased P200 amplitude in the normal subjects (Maby et al., 2004). Then the investigators computed the temporal and spectral correlation coefficients for some individual subjects, using 13 electrodes (Maby et al., 2005). Field exposure altered temporal correlation in 7 of 9 normal subjects (increase in 5, decrease in 2) and in 5 of the 6 epileptics (increase in 2, decrease in 3). Frequency correlation was altered in 8 normal subjects (increase in 5, decrease in 3) and in 5 epileptics (increase in 4, decrease in 1). In their third analysis, the variables were reanalyzed and averaged across all electrodes and all subjects, and the previously reported results were confirmed (Maby et al., 2006).

The large number of variables, and their arbitrariness, obviated the possibility that the conclusions reached by the investigators were reliable. Their strategy of averaging across subjects (Maby et al., 2006) after the results of a prior analysis showed that different subjects responded differently to the fields (Maby et al., 2005) was particularly inexplicable.

Bak et al. (2003) evaluated the effects of 450, 935, and 1,800 MHz mobile-phone EMFs on auditory brain-stem evoked responses measured during and after EMF exposure. Each subject was exposed for 20 min, and the averaged responses were compared across 15 subjects using multiple multiple-factor ANOVAs. No effects on latency were found.

The investigators' avowed goal was to shed light on the problem of why earlier studies of the effects of mobile-phone EMFs on cognitive processing were contradictory. However, brain-stem auditory potentials measure only the rate of neural conduction along the auditory nerve between the ear and the auditory brain-stem; they are not a measure of cognitive processing. The investigators recognized this limitation ("it is noteworthy that the auditory brain stem response reflects the function of only a minor part of the auditory pathway"), but did not reconcile the clear mismatch between their goals and their methods. Further, although they did not evaluate the sensitivity of their experiment, the variance in the data suggested that the investigators would not have detected even clinically significant brain-stem pathology. This report exemplified the meaninglessness of negative studies that also fail to include positive controls or a power analysis.

Eulitz et al. (1998) used an oddball paradigm to measure auditory event-related potentials in the presence and absence of mobile-phone EMFs, but found no effects. When they reanalyzed the data using a time-dependent form of spectral analysis in connection with multiple three-way ANOVAs, one test (18.75–31.25 Hz from the left hemisphere for one of the oddball conditions) was significant. Their conclusion (that the EMFs "alter distinct aspects of the brain's electrical response to acoustic stimuli") was unwarranted because no corrections were made to account for the multiple statistical tests that were performed.

German investigators (Freude et al., 1998) studied the effects of mobile-phone EMFs on manifestations of brain electrical activity that preceded volitional muscle movement (slow potentials); data was obtained from 30 electrodes. The investigators performed 3-way repeated measures ANOVAs; the factors were EMF (on/off), hemisphere (left/right), and brain region (three regions). Various differences for the factors and their interactions were described, and interpreted to mean that there may have been an EMF effect. In two additional experiments (Freude et al., 2000), the investigators described bilateral decreases in average slow potentials from a particular collection of derivations (Figure 3). It seems implausible for such specific effects to have occurred twice by chance. On the other hand, the investigators did not indicate whether the number and identity of the electrodes in each region were chosen before or after the data was collected. Another problem involved the choice of the EEG analysis interval. The slow potentials were averaged over the 500 ms preceding motor activity, even though numerous other averaging intervals were possible; no explanation for that choice was provided. In a previous study not involving EMFs (Freude et al., 1988), the investigators used four different averaging intervals none of which were the same as those used in their EMF experiments (Freude et al., 2000).

Hamblin et al. (2004) investigated the effects of EMFs on auditory event-related potentials in 12 subjects performing an oddball task who were exposed (30 min) and sham-exposed (1 week apart), with the phone mounted on the right side. Peak amplitudes and latencies were extracted for target and non-target stimuli and averaged over 6 head regions. Three-way ANOVA indicated that EMF exposure was

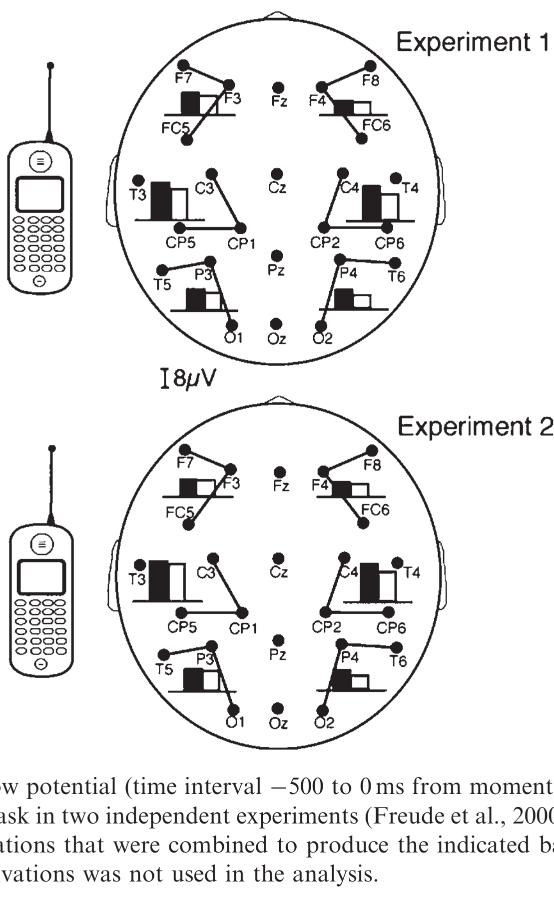

Figure 3. Mean slow potential (time interval −500 to 0 ms from moment of key press) in the visual monitoring task in two independent experiments (Freude et al., 2000). The lines indicate the electrode derivations that were combined to produce the indicated bar graphs. The data from the other derivations was not used in the analysis.

associated with a right-side reduction in amplitude and latency of the N100 wave for non target stimuli and an increase in P300 latency for target stimuli.

In a second study (Hamblin et al., 2006), the specific hypotheses of a reduction of amplitude and latency of N100 to non target stimuli and an increase in P300 latency to target due to EMF exposure were tested. No significant effects were found, and the authors concluded "…the present results detract from the previous positive evidence and we conclude that there is currently no clear evidence in support of a mobile-phone-related EMF effect on event-related potentials." This was one of the few instances where investigators sought to prospectively test a hypothesis gleaned on the basis of a data-mining approach in a prior study. They opined regarding the reasons for their failure to support their hypothesis, but they did not acknowledge that the most probable reason was that the effects of EMFs on brain electrical activity are nonlinearly related to the field, whereas they used linear analysis (ANOVAs).

Jech et al. (2001) investigated the effects of EMFs on event-related potentials recorded during EMF exposure, and on baseline EEG recorded after exposure. The subjects, who were narcoleptics, were either exposed or sham-exposed on successive days. The latencies and amplitudes of various components of the potentials triggered by a visual oddball task were averaged over multiple electrode derivations, and the data was analyzed by three-way multivariate ANOVA for repeated measures; several statistically significant differences were found. There were no after-effects on baseline EEG. The investigators concluded that mobile-phone EMFs might be beneficial because they inhibited excessive sleepiness. However, the few effects claimed could be explained by chance.

Papageorgiou et al. (2006) studied the effect of two auditory stimuli on evoked potentials recorded from 15 electrodes, with and without exposure to an unmodulated 900-MHz EMF (no 217-Hz pulse modulation). Three significant differences in 30 tests were found (family-wise error rate $p = 0.19$), which did not support the conclusion of the investigators that the EMFs had affected cognitive processing.

Hountala et al. (2008) measured spectral power coherence from 15 electrodes during an auditory memory task and concluded that males had more coherence than females in the absence of EMFs, 900-MHz EMFs eradicated the differences, and 1,800-MHz EMFs reversed it (females more coherent). The investigators had previously reported that males had more spectral power, and that during exposure to 900 MHz the power decreased in males and increased in females (Papageorgiou et al., 2004). Gender-based differences in brain electrical activity in non-exposed adult subjects had not previously been established. The putative differences were therefore confounded with the putative effects of the mobile-phone EMFs.

Desynchronization, also called alpha-blocking reactions, is a change in brain activity triggered by external events but not time-locked to them (Lopes da Silva, 1999). Event-related desynchronization is normally used to study cortical activation, consciousness, and processing of sensory information preparatory to executing a motor command (Lopes da Silva, 1999). In a series of experiments, Finnish investigators evaluated the effects of mobile-phone EMF exposure on desynchronization in subjects performing auditory and visual memory tasks (Krause et al., 2000a, 2000b, 2004, 2006, 2007). The exposure and control sessions typically each lasted 30 min during which approximately 200 trials were run and the EEG was recorded from 20 electrodes. Initially the investigators described the occurrence of desynchronization due to an EMF during an auditory memory task, as assessed using 3-way ANOVAs

(Krause et al., 2000a). However, the result was not replicated in a subsequent study that involved 24 subjects (Krause et al., 2004). Desynchronization triggered by a visual memory task was claimed to have occurred in 24 subjects (Krause et al., 2000b). However, the investigators later revealed that the data had been contaminated by an auditory artifact (Krause et al., 2006). They tried again, and claimed to have successfully demonstrated EMF-induced desynchronization in children (Krause et al., 2006) and adults (Krause et al., 2007), performing auditory and visual memory tasks. The effects described were said to depend on details regarding the EMF and on the location of the derivations from which the EEG was recorded. However, both studies were not protected against family-wise error.

Effects During Exposure: Summary

In almost all cases where effects of mobile-phone EMFs on the EEG were claimed, many statistical tests had been performed without adequate protection against chance. Thus, the reports did not provide reliable evidence of an effect of the fields on brain electrical activity. Equally serious was the absence of consideration of the role of electrode artifacts. In general, metallic electrodes connected to high-input-impedance amplifiers like those used to measure the EEG will generate a spike at the input each time the stimulus is applied or removed (Figure 4). The duration of the

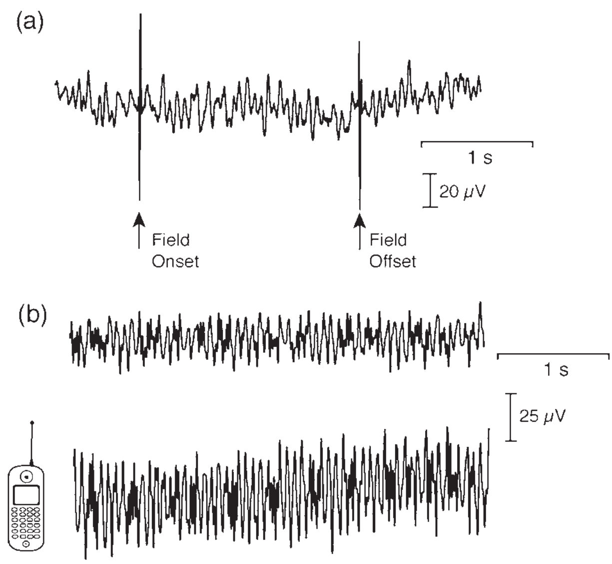

Figure 4. Electrode artifacts created when EEG electrodes are exposed to pulsed electromagnetic fields. (a) Electroencephalogram (C_3, referenced to linked ears) recorded during onset and offset of 2 G, 60 Hz showing the presence of typical spike artifacts (~30 ms); the artifacts also occur as a consequence of application of electric fields. (b) Top, electrical noise from an electrical phantom of the human head. Bottom, signal from the same electrode during exposure to the maximum output of a GSM mobile phone (Nokia 6340i); the electrode was 5 cm from the antenna. The GSM-EMF-induced artifactual signal consisted of multiple onset and offset spikes produced by radio-frequency pulses from the antenna and by low-frequency magnetic fields produced by the battery current (217 Hz, from each source). The signals in (a) and (b) were analog-filtered at 0.5–35 Hz and recorded using an electroencephalograph (Nihon Kohden, Irvine, CA).

artifact (determined by the pass-band of the system and the response characteristics of the amplifier) is approximately 30 ms. In a typical mobile-phone EMF experiment 217 radio-frequency pulses per second were applied to the subject, resulting in 434 electrode spike potentials per second. Because most of the studies also applied a low-frequency magnetic field in addition to the radio-frequency EMFs (Reiser et al., 1995; Carrubba et al., 2007a; Röschke and Mann, 1997; Hietanen et al., 2000; Croft et al., 2002, 2008; D'Costa et al., 2003; Curcio et al., 2005; Mann and Röschke, 1996; Wagner et al., 1998, 2000; Lebedeva et al., 2000, 2001; Maby et al., 2004, 2005, 2006; Bak et al., 2003; Eulitz et al., 1998; Freude et al., 1998, 2000; Hamblin et al., 2004, 2006; Jech et al., 2001; Krause et al., 2000a, 2000b, 2004, 2006, 2007), the problem of artifacts was compounded because the magnetic field from the battery current also produces 434 spikes/s. No investigator removed these artifacts prior to decomposing the recorded signal into its component frequencies. Indeed, only one investigator explicitly indicated that the artifacts existed (Perentos et al., 2007). In the baseline EEG studies, the spectral energy in the spikes was folded into the true brain signal when the signal was decomposed, and could have accounted for the reported significant differences.

It might be suggested that the problem of spike artifacts did not obfuscate the meaning of the event-related studies because the induced potentials were computed by means of time averaging and therefore would have been distinguishable from the spike potentials. However, the induced potentials occurred several hundred milliseconds after the onset of the stimulus, but *during* the application of the GSM EMF stimulus. Consequently the EEG contained both the temporally locked response to the visual or auditory stimulus as well as the temporally locked spike response due to the GSM EMF stimulus. Thus the event-related studies were also contaminated by artifacts.

Many reports employed linear analysis (ANOVA) and concluded that mobile-phone EMFs increased alpha activity in the EEG (Reiser et al., 1995; Croft et al., 2002; D'Costa et al., 2003; Curcio et al., 2005; Hinrikus et al., 2004). However, sensory stimuli produce both *increases and decreases* in brain alpha, depending on the subject (Shaw, 2003). Use of ANOVA to detect stimulus-induced changes in that kind of a dependent variable is strongly contraindicated because of the likelihood ANOVA would average away real effects. The thing to be explained, therefore, is why so many investigators reported observing what is likely a non existent phenomenon. Our explanation is that the claims resulted from the use of data-mining to make meaning from the cata.

Effects After Exposure

Vecchio et al. (2007) measured the EEG 5 min before and 5 min after exposing 10 subjects for 45 min (only males, to avoid potential hormonal effects). During the exposure the subjects were able to move around the experimental room and chat with the investigators, who attempted to regulate the amount of talking, walking, and the content of the conversation so that emotional arousal was not produced. The linear coherence (a measure of the coupling between two signals at a given frequency) among 4 pairs of electrodes was calculated and evaluated using a 3-way ANOVA. An interaction between condition (exposure or sham exposure) and electrode pair was found, which the investigators interpreted to indicate an effect of the EMF on inter-hemispherical coupling of EEG rhythms. However, even assuming the statistical reliability of their interpretation, the uncontrolled activity of the subjects could plausibly have accounted for it.

Regel et al. (2007a) exposed 24 subjects for 30 min to either pulse-modulated or continuous wave EMFs and compared the EEG recorded prior to exposure with that from 0, 30, and 60 min after exposure using multiple 3-way ANOVAs. They claimed increased power only at 10.5–11 Hz, only at 30 min, only for the pulsed field, and only after ignoring the potential role of chance.

Perentos et al. (2007) studied 12 subjects who were exposed for 15 min. The EEG (16 channels) was analyzed immediately after EMF exposure because spike artifacts were present in the EEG signal measured during exposure. No change in EEG power in any frequency band was seen.

Several reports involved the effects of mobile-phone EMFs on the EEG during sleep (Huber et al., 2000, 2002; Loughran et al., 2005; Regel et al., 2007b; Hung et al., 2007). Huber et al. (2000) exposed 16 subjects for 30 min during an awake period prior to a 3-h sleep episode and found an increased power in some of the alpha frequencies during the first 30 min of non-REM sleep. Loughran et al. (2005) repeated the study and also found increased alpha power from the same two derivations (C_3 and C_4) (although not at the same frequencies). Taken together the reports suggested a time-dependent after-effect. However, neither study was adequately protected against family-wise error because 3 significant differences could have occurred by chance in 24 tests (8–14 Hz, 0.25 Hz bins) in two independent studies). In a similar experiment, Huber et al. (2002) found an after-effect on alpha power in stage two sleep. Regel et al. (2007b) repeated the study and found an increase in some alpha frequencies in non-REM sleep, but not in stage two sleep.

Hung et al. (2007) exposed subjects for 30 min and reported increased delta power during the subsequent 90 min, but only in 1 of 6 derivations.

Three reports failed to find an effect of mobile-phone EMFs on auditory brainstem evoked potentials; Stefanics et al. (2007) and Parazzini et al. (2007) after 10 min exposure, and Arai et al. (2003) after 30 min exposure.

In a series of experiments, Japanese investigators asked whether 30 min exposure to GSM mobile phones (800 MHz, 0.8 maximum output power) altered post-exposure human brain activity (Yuasa et al., 2006; Terao et al., 2007; Inomata-Terada et al., 2007). The exposure did not affect somatosensory evoked potentials (Yuasa et al., 2006), the frequency of visual saccades (Terao et al., 2007), or motor evoked potentials elicited by pulse transcranial magnetic stimulation (a result that was not surprising even to the investigators; Inomata-Terada et al., 2007).

Magnetoencephalography involves the recording of weak magnetic fields outside the head; it is a far rarer method than the EEG for characterizing brain electrical activity but may have some theoretical advantages for understanding brain function (Lopes da Silva, 1999). Hinrichs and Heinze (2004) employed magnetoencephalography to study the effects of mobile-phone EMFs on memory encoding, using an encoding-retrieval paradigm. The subjects were exposed to the field while they memorized a list of words and then were asked to recall specific words. The EMF exposure altered the amplitude of the event-related magnetic field, but only within a narrow latency range that was identified by data-mining.

Effects After Exposure: Summary

The advantage of after-effects experiments was that they obviated the problem of electrode artifacts. The disadvantage (in addition to those discussed in connection with the during-exposure experiments) was that the after-effect design undercut the rationale for studying EMF effects on brain electrical activity. In the reports discussed previously, the EMFs were physically present in the brain during all immediate early biological events including putative signal transduction, generation and propagation of an afferent signal, and signal processing at various levels of brain organization. At least in principle, therefore, the studies were pertinent to the hypothesis that mobile-phone EMFs affected cognitive processing. The after-effects studies, in contrast, were bioassays at best because there was simply no way of ever knowing whether any observed changes were simply general metabolic effects or specific effects on the brain. Bioassay experiments were appropriate at the dawn of the EMF health-hazards issue (Marino and Becker, 1982a), but they no longer serve any important purpose because it is now universally agreed that EMFs *can* cause biological effects—further affirmative answers to the *can* question are unneeded. The present task is to conduct hypothesis-driven studies that help provide a deeper understanding of particular effects.

Discussion

Analysis of Reports

A fundamental and characteristic scientific limitation in the reports was that the experiments were based on an incorrect electrophysiological model of the brain, that its electrical activity was in equilibrium with its surroundings. For a given subject, the instantaneous values of the dependent variables (spectral power, evoked potentials, slow potentials, for example) measured and/or computed from various scalp derivations were assumed to be stationary, and therefore representable by a time-average value. Inter-subject differences were conceptualized as a Boltzmann distribution that could be represented by a grand average. In this perspective, one in which dynamical activity had no physiological significance, the effect of mobile-phone EMFs on the brain could be (and was) assessed using ANOVAs (or other linear statistics) to determine whether the grand average differed between the presence and absence of the field, or between pre- and post-exposure. This model was adopted in all but four reports (Lebedeva et al., 2000, 2001; Bachmann et al., 2005; Hinrikus et al., 2007), even though it was antithetical to the accepted view of brain function (Adolphs et al., 2005; Basar, 2004; Freeman, 2007; Fuster, 2000; Heb, 1980; LaMotte and Mountcastle, 1975; Lashley et al., 1951; Regan, 1989; Sporns et al., 2000). The brain is not in equilibrium with its environment, the EEG is not stationary, and the effects on brain electrical activity are not linearly related to EMFs (see below). From the beginning, therefore, the possibility that the experiments could provide reliable information was nil because their foundational assumption was inconsistent with how the brain works.

We showed that magnetic fields comparable in frequency and strength to those produced by the battery current in GSM mobile phones consistently caused changes in brain electrical activity in human subjects, and that the changes could be detected only when the EEGs were analyzed using nonlinear methods (Carrubba and Marino, 2008; Carrubba et al., 2006, 2007a, 2007b, 2008a, 2008b; Marino et al., 2004). Whether brain electrical activity is also affected by radio-frequency GSM EMFs is an empirical question. Based on results involving older mobile-phone technology (Marino et al., 2003), a model of a candidate transduction mechanism (Kolomytkin et al., 2007), and empirical observations that the frequency of an EMF is not a primary factor in determining the resulting biological effects (Marino and Becker, 1982a), we think that properly designed and performed studies likely will reveal that mobile-phone radiofrequency EMFs consistently affect human brain electrical activity. If an unmodulated high-frequency mobile-phone field is applied via an antenna, an onset evoked potential with a latency of 100–400 ms will occur, depending on the subject. If the field is maintained *beyond* the decay of the onset potential, an effect on brain activity due to the presence of the EMF will be observed, and will persist for the duration of the stimulus (Carrubba et al., 2006, 2008b). When the mobile-phone field is terminated, an offset evoked potential occurring 100–400 ms later will also be detected (Carrubba et al., 2006). If the field is applied as a brief pulse, say 50 ms, as is commonly the case in evoked-potential studies, then field-induced evoked potentials consisting of superimposed onset and offset effects will be observed with a latency of 100–500 ms, depending on the subject (Carrubba et al., 2008a). Nonlinear analytical techniques are a prerequisite for observing reproducible effects of GSM EMFs on human brain electrical activity; recurrence quantification analysis is one such technique (Carrubba and Marino, 2008; Carrubba et al., 2006, 2007a, 2007b, 2008a, 2008b; Marino et al., 2004).

Even if nonlinear analysis were employed, it would not be a substitute for a reasonable experimental design—both elements are needed. For example, when a high-frequency mobile-phone EMF is applied in a manner that simulates normal phone use (multiple bursts of high-frequency energy over a period on the order of minutes), a nonlinear combination of numerous repetitions of the elemental process described can be expected. The experimental design must therefore accommodate this complexity. If the high-frequency EMF is applied by means of a mobile phone, additional complex effects due to the battery-current magnetic field can be anticipated. If the EMF exposure takes place while the subject is cognitively processing auditory or visual information, still further complexity is unavoidable. Use of idiosyncratic experimental designs (Freude et al., 1988, 1998, 2000; Krause et al., 2000a, 2000b, 2004, 2006, 2007) or novel dependent variables (Hountala et al., 2008; Papageorgiou et al., 2004) are also complicating factors.

The consistent absence of due regard for family-wise error in evaluating the meaning of the statistical tests was another serious problem. When many statistical tests are performed to examine the hypothesis that mobile-phone EMFs altered brain electrical activity, and one test is significant at $p < 0.05$, rejection of the null hypothesis is not justified at a confidence level of $P_{FW} < 0.05$. A variety of verbal formulas were used to express a conclusion that mobile-phone EMFs had altered brain electrical activity. As examples, investigators asserted that EMFs caused "…clear tendencies…" (Hinrikus et al., 2004), "…induced but not evoked brain potential activity…" (Eulitz et al., 1998), "…a significant decrease of slow potentials…" (Freude et al., 2000), "…improve(d) performance…" (Jech et al., 2001), "…a gender-related influence on brain activity…" (Papageorgiou et al., 2004), "…altered (desynchronization) responses…" (Krause et al., 2000b), "…effects on brain oscillatory responses…" (Krause et al., 2006), a "(modified)…sleep electroencephalogram…" (Loughran et al., 2005), "…a dose-dependent increase of power…" (Regel et al., 2007b). The formulas were misleading because they obscured the fact that the associated level of chance was greater than 5%.

A third problem involved the experiments where the EEG was measured *during* field exposure to mobile-phone EMFs. Whenever a subject with scalp electrodes is exposed to an EMF, the possibility must at least be considered that the onset and offset of the field triggered a spike artifact at the input of the EEG amplifier (Figure 4). Many factors including the power density of the EMF, the spatial relation between the electrodes and the antenna, and the characteristics of the measuring circuitry will affect the detectability of the spike artifacts. The point is not that they will always occur, but rather that their possible presence must be assessed in each study. The artifacts may be identified and removed prior to data analysis, excluded as a likely source of error on the basis of proper argument, or acknowledged as a valid alternative explanation to a claimed EMF-induced physiological effect. To ignore the artifact issue, however, is impermissible. Yet the issue was ignored in almost all the reports, and was not adequately addressed in even one case. The presence of the spikes constituted an alternative explanation for each of the claims of positive effects that were based on statistically significant differences between EEGs compared in the presence and absence of GSM EMFs.

Fourth, with few exceptions, the investigators did not employ positive or negative controls. Thus, where an effect was claimed, the absence of sham experiments (sham-exposure compared with its corresponding control) left open the possibility that the claimed effect was attributable to the analytical techniques used, which in some cases were so complex as to beggar description (Maby et al., 2004, 2005, 2006). The absence of positive controls essentially eliminated any potential value in the 18 negative studies (Table 1) because, for all we know, no non lethal stimulus could have produced significant differences in the dependent variables. This consideration is particularly applicable to the brain-stem auditory evoked potential studies (Bak et al., 2003; Stefanics et al., 2007; Parazzini et al., 2007; Arai et al., 2003), which were all negative and could hardly have been otherwise.

A fifth problem was that many of the reports violated an important, commonsense principle for laboratory experiments pertinent to public health. Given the implications of any positive findings, it was only reasonable that the experimental design should be clear in the sense that it was commonly used by workers in the area to study non-EMF questions. In other words, the novelty aspect should have been limited to the question studied, and should not have included the methodology or experimental design. However, many investigators devised novel methods (Bachmann et al., 2005; Hinrikus et al., 2007), or studied the effects of GSM EMFs on phenomena that themselves were not established (Hountala et al., 2008; Papageorgiou et al., 2004). Such unorthodoxy was almost guaranteed to generate uncertainty, regardless of the results of the experiment.

Overall, the reports were attempts to study a nonlinear phenomenon using linear methods without proper controls while failing to consider experimental artifacts or the role of chance. Although 37 of the 55 reports were self designated as positive (Table 1), the actual number of positive reports was probably far smaller, and may have been zero.

A sociological study concluded that the results of experiments funded by the mobile-phone industry were significantly more likely to be negative ($p < 0.05$) compared with experiments funded by non industry sources (Huss et al., 2007). Our analysis pointed to a more basic problem. Evaluating the "positive" or "negative" status of a report is not simply a matter of counting beans added to a pot—the quality of the report must also be evaluated. In the present case, the actual number of negative reports was far higher than the number of beans in the negative pot.

Manufactured Doubt

To assess who bore primary responsibility for the generally poor quality of the research involving the effects of GSM EMFs on human brain activity (Table 1),

Table 1

Reports involving the effects of GSM electromagnetic fields on human brain electrical activity. $N = 55$. F, foundation; R, research. $+(-)$, study self-reported as positive (negative)

Ref no. [Claim]	Support
(Papageorgiou et al., 2006)[+]	AstraZeneca Hellas
(Croft et al., 2002)[+]	Clarus Products
(Jech et al., 2001)[+]	COST281 (F. Funk)
(Bak et al., 2003)[−]	EARnEARE (Nokia)
(Hinrikus et al., 2004)[+], (Hinrikus et al., 2008b)[+], (Bachmann et al., 2005)[+], (Hinrikus et al., 2007)[+], Hinrikus et al., 2008a[+]	Estonian Science F.
(Regel et al., 2007a)[+], (Huber et al., 2000[+], (Huber et al., 2002)[+]	Foundation for R.
(Eulitz et al., 1998)[+]	German R. F.
(Reiser et al., 1995)[+], (Röschke and Mann, 1997)[−], (Mann and Röschke, 1996)[+], (Wagner et al., 2000)[−], (Wagner et al., 1998)[−], (Lebedeva et al., 2000)[+], (Lebedeva et al., 2001)[+], (Freude et al., 1998)[+], (Freude et al., 2000)[+]	German Telekom
(Hountala et al., 2008)[+], (Papageorgiou et al., 2004)[+]	Greek Ministry
(Stefanics et al., 2007)[−], (Parazzini et al., 2007)[−]	Guard (Nokia)
(Vecchio et al., 2007)[+]	Italian Telecom
(Hinrichs and Heinze, 2004)[+]	KPN Mobile
(Regel et al., 2007b)[+]	Mobile Communication F.
(Maby et al., 2004)[+], (Maby et al., 2005)[+], (Maby et al., 2006)[+]	Mobile Communications Consortium
(Hung et al., 2007)[+]	Mobile Phone R.
(Curcio et al., 2005)[+]	Motorola
(Krause et al., 2000a)[+], (Krause et al., 2004)[−], (Krause et al., 2000b)[+], (Krause et al., 2006)[+]	Nokia
(Fritzer et al., 2007)[−]	Radio R.
(Perentos et al., 2007)[−]	Radiofrequency R. Center
(Arai et al., 2003)[−], (Yuasa et al., 2006)[−], (Terao et al., 2007)[−], (Inomata-Terada et al., 2007)[−]	Radio-industry & business committee
(Krause et al., 2007)[−]	R. Association for Radio Applications
(Loughran et al., 2005)[+]	R. Council (Nokia)
(Kleinlogel et al., 2008b)[−], (Kleinlogel et al., 2008a)[−], (Borbély et al., 1999)[+], (Huber et al., 2003)[+]	Swisscom
(Hietanen et al., 2000)[−]	Tech. Dev. Center
(D'Costa et al., 2003)[+], (Croft et al., 2008)[+], (Hamblin et al., 2004)[+], (Hamblin et al., 2006)[−]	Telstra R. Laboratories

we analyzed who authorized the reports. They were all funded, wholly or partially, by the mobile-phone industry (MPI), with only seven apparent exceptions (Bachmann et al., 2005; Hinrikus et al., 2004, 2007, 2008a, 2008b; Papageorgiou et al., 2006; Hountala et al., 2008).

Did the MPI's choice of research projects indicate a plan to legitimize its knowledge claims (Balzano and Swicord, 2008; Chou, 2003; Glaser, 2007; Valberg et al., 2007)? The infrastructure needed to implement such a goal has been in place, as evidenced by organizations including the Mobile Manufacturers Forum and the funding entities in which Forum members are represented. To answer the question, we examined the characteristics of the brain-activity studies and the normative framework in which they were embedded.

Of the 48 studies supported by the MPI (Table 1), 30 were positive and 18 were negative (38% negative), including 4 studies that claimed to have proved the null hypothesis (Röschke and Mann, 1997; Bak et al., 2003; Stefanics et al., 2007; Arai et al., 2003); all 7 studies not funded by the MPI were positive. Although the industry-funded studies were significantly more likely to be negative ($p < 0.05$, chi-square), as expected (Huss et al., 2007), no two positive studies reported the same effect, and the few attempts to do so failed. Thus the apparent message of the studies (Table 1) dovetailed well with the MPI position that there are no reproducible biological effects (Balzano and Swicord, 2008; Chou, 2003; Glaser, 2007; Valberg et al., 2007), and did so without denying the existence of EMF-induced bioeffects, which was the tactical error made by the electric power industry 30 years ago. If the investigators funded by the MPI had published only negative studies, the industry research program would not have passed the laugh test. Conversely, if all the studies were positive, the industry's story (Glaser, 2007) would have been seriously undercut. Sixty-two percent positive served to both protect the interests of the industry and still sustain the appearance that its position (Balzano and Swicord, 2008; Chou, 2003; Glaser, 2007; Valberg et al., 2007) was based on scientific experiments.

The legitimization process had the hallmark of a well-designed legal strategy. Any peer-reviewed report claiming to have shown that mobile-phone EMFs affected brain electrical activity, particularly a report funded by the MPI, is potential evidence in a court case on behalf of a party adverse to the industry. Inclusion of a disclamatory statement in the original publication is a strategy that tends to blunt such uses by a plaintiff. Of the 30 MPI-funded studies that were self-designated as positive, 22 contained a disclamatory statement (Reiser et al., 1995; Croft et al., 2002, 2008; D'Costa et al., 2003; Curcio et al., 2005; Mann and Röschke, 1996; Maby et al., 2004, 2005, 2006; Eulitz et al., 1998; Freude et al., 1998, 2000; Hamblin et al., 2004; Krause et al., 2000a, 2000b, 2006; Regel et al., 2007a; Huber et al., 2000, 2002, 2003; Loughran et al., 2005; Hinrichs and Heinze, 2004). For example, "The alpha changes…reported in this study have not previously, or in this study, been found to relate to health outcomes" (Croft et al., 2008); "Conclusions about possible health consequences are premature, particularly with respect to chronic and/or repeated exposures" (Curcio et al., 2005); "This study does not allow us to determine any health risks" (Eulitz et al., 1998); "(The results) do not allow any conclusions to be drawn concerning human well-being and health" (Freude et al., 2000); "Adverse health effects cannot be derived from these data" (Hinrichs and Heinze, 2004); "Conclusions about possible adverse effects on human health are premature because underlying mechanisms are unknown" (Huber et al., 2000); "The present results do not allow any conclusions concerning the possible effects of long-term cellular phone use on cognition or health" (Krause et al., 2006); "The relevance of our results concerning possible health hazards cannot be assessed yet" (Mann and Röschke, 1996); "No statement can be given as to whether a positive or negative influence exists with respect to human health" (Reiser et al., 1995).

From a scientific perspective the disclamatory statements were puerile, and it would be naïve to suppose that so many investigators spontaneously decided to include them. More likely, the disclaimers were explicit or implicit requirements of the funder, with or without the agreement of the authors (Ivaschuk et al., 1997; Cribb and Hamilton, 2005).

The cognitive framework within which the reports were embedded increased the likelihood of acceptance of the MPI claims. One element was the assumption that the problem of mobile-phone EMF effects on the brain bore no relation to the EMF-induced effects on the brain observed at other frequencies. Consistent with this approach, the mobile-phone brain-activity investigators did not reference or explicitly consider any reports from outside the telecommunications orbit, as if there was something special about the EMF frequencies used by the MPI.

Another element in the framework was the concept that "each mobile phone has a unique footprint of exposure and significantly differs from phone to phone" (Boutry et al., 2008), and that "biological studies must reflect the intricate details of the various (mobile phone) systems" (Pederson and Anderson, 1999). Consistent with this notion, the reports contained extensive mobile-phone engineering mumbo-jumbo (Hietanen et al., 2000; Kleinlogel et al., 2008a; Huber et al., 2003; Krause et al., 2004; Parazzini et al., 2007), even though there is not a scintilla of evidence suggesting that the language had any significant biological meaning.

The use of specific absorption rate deserves special mention because, along with appeals to the authority of expert groups controlled by the MPI (see below), elevation of the specific absorption rate to a level of seeming importance has been the industry's most important stratagem for controlling the text of the mobile-phone health-risk issue. In experiments involving deterministic consequences of EMFs, the normal practice is to state the independent variable in terms of the variables in Maxwell's equations, which are electric field, **E** , magnetic field, **B** , and frequency. Even though the wavelength of mobile-phone radiation is such that the brain of a normal user is in the near field of the phone's antenna (OSHA, 1990), a long-standing practice has been to use the plane-wave approximation ($E^2/377$) (Marino and Becker, 1982a, 1982b) and express the applied field in terms of a power density. Many investigators eschewed use of a Maxwellian variable, and instead listed only a specific absorption rate (Hietanen et al., 2000; Croft et al., 2008; Fritzer et al., 2007; Kleinlogel et al., 2008a, 2008b; Wagner et al., 1998, 2000, Borbély et al., 1999; Huber et al., 2003; Maby et al., 2004, 2005, 2006; Freude et al., 1998; Hamblin et al., 2006; Jech et al., 2001; Perentos et al., 2007; Regel et al., 2007a, 2007b; Huber et al., 2000, 2002; Loughran et al., 2005; Hung et al., 2007; Stefanics et al., 2007; Parazzini et al., 2007; Hinrichs and Heinze, 2004), as if it were true that the extent of the ability of the EMF to heat water was a proper description of their independent variable—it was not. The specific absorption rate has been adopted by regulatory agencies to compare the outputs of mobile phones, but no authority has used it to explain their neurophysiological consequences. There are two good reasons why this is the case: (1) there is no known relationship; (2) not surprisingly, brain electrical activity is more sensitive to mobile-phone EMFs when the brain is directly irradiated compared with, for example, irradiation of the back muscles (Marino et al., 2003). Use of specific absorption rate misdirects attention from the subject's brain to the mobile phone itself, thereby advantaging the industry. The likely explanation for why many investigators improperly characterized the applied EMF was that the funder expected them to conform to the aspect of the MPI's comprehensive socio-cognitive framework that regarded as biologically meaningful the specific absorption rate of mobile-phone EMFs.

A historically effective way to legitimize knowledge claims is to support experts or organizations that will favor one's point of view. When the *quid pro quo* relationships are undisclosed, the practice is unacceptable. The 55 reports (Table 1) were published in 21 journals, but in no case did the investigators reveal whether anything of value had been received from the study sponsor. The website for the Mobile Manufacturers Forum contains links to 151 "expert group and independent authority statements" that support the MPI knowledge claims (Balzano and Swicord, 2008; Chou, 2003; Glaser, 2007; Valberg et al., 2007); many investigators (Table 1) are associated with these 151 groups. The need for transparency regarding funding of mobile-phone studies, and how meaning is attached to them, has been pointed out previously (Hardell et al., 2007).

Information regarding the nexus between EMF experts and the MPI could cause some authorities to alter their opinion of health dangers. According to the Mobile Manufacturers Forum, the Food and Drug Administration (FDA) concluded that "the scientific evidence does not show a danger to users of wireless phones, including children and teenagers" (MMF, 2008). The data we found is consistent with the idea that the FDA is presently satisfied; the experiments (Table 1) were conducted in Europe (44 studies), Australia (7 studies), and Japan (4 studies); none were from the United States. The question, however, is whether the FDA has been misled. Had the FDA known that some investigators had received something of value from the MPI, the FDA might have formed a different opinion regarding the safety of mobile-phone EMFs.

Nothing is more important for legitimizing knowledge claims than publication in peer-reviewed journals. Most of the journals that published the 48 MPI-sponsored reports published only one report; *Bioelectromagnetics* published 16. Of this total, 7 were positive and 9 were negative; all other journals combined published 39 reports, 30 of which were positive and only 9 of which were negative, indicating that reports in *Bioelectromagnetics* were more likely to be negative ($p < 0.05$, chi-square). None of the negative reports had positive controls or a power analysis. Anybody can find nothing, so it is difficult to discern a scientific reason for why the journal published nine reports that had negligible scientific value. Among the deep, long-standing connections between the MPI and the Bioelectromagnetics Society was the "Gold" sponsorship of its annual meetings in 2006–2008 by the Mobile Manufacturers Forum. These circumstances create the appearance that the MPI point-of-view received unmerited consideration, whether or not it actually occurred.

Bartleby

There is a pressing need for properly designed laboratory experiments as part of an overall plan to evaluate the safety of mobile-phone EMFs on the basis of controlled scientific studies. No alternative exists that is both scientific and ethical. The Interphone Study, for example, will likely not answer the public-health question because the meaning of every epidemiological study is always already deferred. In addition, a premeditated plan to condition public warnings regarding mobile-phone EMFs on the future acquisition of data from persons who have not consented to serve as research subjects amounts to involuntary human experimentation. We obtained permission from our institutional review board for human research and from our subjects for our EMF brain-activity experiments, and we think *all* EMF investigators have a similar obligation. Laboratory experiments involving the effect of GSM EMFs on human brain electrical activity are particularly important because positive results would immediately raise an imperative for purposes of public-health planning: should those effects be assumed to be safe or unsafe? Unfortunately, when the mobile-phone industry was asked to fund reliable experiments, it effectively answered as did Herman Melville's Bartleby (Melville, 2004): ''We would prefer not to.''

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References

Adolphs, R., Tranel, D., Koenigs, M., Damasio, A. R. (2005). Preferring one taste over another without recognizing either. *Nat. Neurosci.* 8:860–861.

Arai, N., Enomoto, H., Okabe, S., et al. (2003). Thirty minutes mobile phone use has no short-term adverse effects on central auditory pathways. *Clin. Neurophysiol.* 114:1390–1394.

Bachmann, M., Kalda, J., Lass, J., et al. (2005). Non-linear analysis of the electroencephalogram for detecting effects of low-level electromagnetic fields. *Med. Biol. Eng. Comput.* 43:142–149.

Bak, M., Sliwinska-Kowalska, M., Zmyslony, M., Dudarewicz, A. (2003). No effects of acute exposure to the electromagnetic field emitted by mobile phones on brainstem auditory potentials in young volunteers. *Int. J. Occup. Med. Environ. Health* 16:201–208.

Balzano, Q., Swicord, M. (2008). Comments on Neurophysiological effects of mobile phone electromagnetic fields on humans: A comprehensive review. *Bioelectromagnetics* 29:410.

Basar, E. (2004). *Memory and Brain Dynamics: Oscillations Integrating Attention, Perception, Learning, and Memory*. Boca Raton, FL: CRC Press.

Borbély, A. A., Huber, R., Graf, T., et al. (1999). Pulsed high-frequency electromagnetic field affects human sleep and sleep electroencephalogram. *Neurosci. Lett.* 275:207–210.

Boutry, C. M., Kuehn, S., Achermann, P., et al. (2008). Dosimetric evaluation and comparison of different RF exposure apparatuses used in human volunteer studies. *Bioelectromagnetics* 29:11–19.

Carrubba, S., Frilot, C., Chesson, A., Marino, A. A. (2006). Detection of nonlinear event-related potentials. *J. Neurosci. Meth.* 157:39–47.

Carrubba, S., Frilot, C., Chesson, Jr., A. L., Marino, A. A. (2007a). Evidence of a nonlinear human magnetic sense. *Neuroscience* 144:356–367.

Carrubba, S., Frilot, C., Chesson, Jr., A. L., Marino, A. A. (2007b). Nonlinear EEG activation by low-strength low-frequency magnetic fields. *Neurosci. Lett.* 417:212–216.

Carrubba, S., Frilot, C., Chesson, Jr., A. L., et al. (2008a). Magnetosensory evoked potentials: Consistent nonlinear phenomena. *Neurosci. Res.* 60:95–105.

Carrubba, S., Frilot, C., Chesson, A., Marino, A. A. (2008b). Method for detection of changes in the EEG induced by the presence of sensory stimuli. *J. Neurosci. Meth.* 173:41–46.

Carrubba, S., Marino, A. A. (2008). The effects of low-frequency environmental-strength electromagnetic fields on brain electrical activity: a critical review of the literature. *Electromagn. Biol. Med.* 27:83–101.

Chou, C. K. (2003). Basic problems of diversely reported biological effects of radio frequency fields. *Radiats. Biol. Radioecol.* 43:512–518.

Cribb, R., Hamilton, T. (2005). Is her cellphone safe? *Toronto Star*, July 11.

Croft, R. J., Chandler, J. S., Burgess, A. P., et al. (2002). Acute mobile phone operation affects neural function in humans. *Clin. Neurophysiol.* 113:1623–1632.

Croft, R. J., Hamblin, D. L., Spong, J. (2008). The effect of mobile phone electromagnetic fields on the alpha rhythm of human electroencephalogram. *Bioelectromagnetics* 29:1–10.

Curcio, G., Ferrara, M., Moroni, F., et al. (2005). Is the brain influenced by a phone call? An EEG study of resting wakefulness. *Neurosci. Res.* 53:265–270.

D'Costa, H., Trueman, G., Tang, L., et al. (2003). Human brain wave activity during exposure to radiofrequency field emissions from mobile phones. *Australas. Phys. Eng. Sci. Med.* 26:162–167.

Eulitz, C., Ullsperger, P., Freude, G., Elbert, T. (1998). Mobile phones modulate response patterns of human brain activity. *Neuroreport* 9:3229–3232.

Freeman, W. J. (2007). The place of "codes" in nonlinear neurodynamics. *Prog. Brain Res.* 165:447–462.

Freude, G., Ullsperger, P., Eggert, S., Ruppe, I. (1998). Effects of microwaves emitted by cellular phones on human slow brain potentials. *Bioelectromagnetics* 19:384–387.

Freude, G., Ullsperger, P., Eggert, S., Ruppe, I. (2000). Microwaves emitted by cellular telephones affect human slow brain potentials. *Eur. J. Appl. Physiol.* 81:18–27.

Freude, G., Ullsperger, P., Krüger, H., Pietschmann, M. (1988). The Bereitschaftspotential in preparation to mental activities. *Int. J. Psychophysiol.* 6:291–297.

Fritzer, G., Goder, R., Friege, L., et al. (2007). Effects of short- and long-term pulsed radiofrequency electromagnetic fields on night sleep and cognitive functions in healthy subjects. *Bioelectromagnetics* 28:316–325.

Fuster, J. M. (2000). Cortical dynamics of memory. *Int. J. Psychophysiol.* 35:155–164.

Garg, V. K., Wilkes, J. E. (1998). *Principles and Applications of GSM*. New York: Prentice Hall.

Glaser, R. (2007). 15 years on biomedical mobile: A story of success. *Q. Bull. Res. Assoc. Radio Applic.* 3:20–27.

Hamblin, D. L., Croft, R. J., Wood, A. W., et al. (2006). The sensitivity of human event-related potentials and reaction time to mobile phone emitted electromagnetic fields. *Bioelectromagnetics* 27:265–273.

Hamblin, D. L., Wood, A. W., Croft, R. J., Stough, C. (2004). Examining the effects of electromagnetic fields emitted by GSM mobile phones on human event-related potentials and performance during an auditory task. *Clin. Neurophysiol.* 115:171–178.

Hardell, L., Walker, M. J., Walhjalt, B., et al. (2007). Secret ties to industry and conflicting interests in cancer research. *Amer. J. Ind. Med.* 50:227–233.

Heb, D. O. (1980). *Essay on Mind.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Hietanen, M., Kovala, T., Hamalainen, A.-M. (2000). Human brain activity during exposure to radiofrequency fields emitted by cellular phones. *Scand. J. Work Environ. Health* 26:87–92.

Hinrichs, H., Heinze, U. J. (2004). Effects of GSM electromagnetic field on the MEG during an encoding-retrieval task. *Neuroreport* 15:1191–1194.

Hinrikus, H., Bachmann, M., Kalda, J., et al. (2007). Methods of encephalographic signal analysis for detection of small hidden changes. *Nonlinear Biomed. Phys.* 1:9.

Hinrikus, H., Bachmann, M., Lass, J., et al. (2008a). Effect of low frequency modulated microwave exposure on human EEG: Individual sensitivity. *Bioelectromagnetics* 29:527–538.

Hinrikus, H., Bachmann, M., Lass, J., et al. (2008b). Effect of 7, 14 and 21 Hz modulated 450 MHz microwave radiation on human electroencephalographic rhythms. *Int. J. Radiat. Biol.* 84:69–79.

Hinrikus, H., Parts, M., Lass, J., Tuulik, V. (2004). Changes in human EEG caused by low level modulated microwave stimulation. *Bioelectromagnetics* 25:431–440.

Hountala, D. C., Maganioti, E. A., Papageorgiou, C. C., et al. (2008). The spectral power coherence of the EEG under different EMF conditions. *Neurosci. Lett.* 441:188–192.

Huber, R., Graf, T., Cote, K. A., et al. (2000). Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG. *Neuroreport* 11:3321–3325.

Huber, R., Schuderer, J., Graf, T., et al. (2003). Radio frequency electromagnetic field exposure in humans: Estimation of SAR distribution in the brain, effects on sleep and heart rate. *Bioelectromagnetics* 24:262–276.

Huber, R., Treyer, V., Borbely, A. A., et al. (2002). Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. *J. Sleep Res.* 11:289–295.

Hung, C. S., Anderson, C., Horne, J. A., McEvoy, P. (2007). Mobile phone 'talk-mode' signal delays EEG-determined sleep onset. *Neurosci. Lett.* 421:82–86.

Huss, A., Egger, M., Hug, K., et al. (2007). Source of funding and results of studies of health effects of mobile phone use: Systematic review of experimental studies. *Environ. Health Persp.* 115:1–4.

Inomata-Terada, S., Okabe, S., Arai, A., et al. (2007). Effects of high frequency electromagnetic field (EMF) emitted by mobile phones on the human motor cortex. *Bioelectromagnetics* 28:553–561.

Ivaschuk, O. I., Jones, R. A., Ishida-Jones, T., et al. (1997). Exposure of nerve growth factor-treated PC12 rat pheochromocytoma cells to a modulated radiofrequency field at 836.55 MHz: Effects on c-*jun* and c-*fos* expression. *Bioelectromagnetics* 18:223–229.

Jech, R., Šonka, K., Růžiča, E., et al. (2001). Electromagnetic field of mobile phones affects visual event related potential in patients with narcolepsy. *Bioelectromagnetics* 22:519–528.

Kleinlogel, H., Dierks, T., Koenig, T., et al. (2008a). Effects of weak mobile phone electromagnetic fields (GSM, UMTS) on well-being and resting EEG. *Bioelectromagnetics* 29:479–487.

Kleinlogel, H., Dierks, T., Koenig, T., et al. (2008b). Effects of weak mobile phone electromagnetic fields (GSM, UMTS) on event related potentials and cognitive functions. *Bioelectromagnetics* 29:488–497.

Kolomytkin, O. V., Dunn, S., Hart, F. X., et al. (2007). Glycoproteins bound to ion channels mediate detection of electric fields: A proposed mechanism and supporting evidence. *Bioelectromagnetics* 28:379–385.

Krause, C. M., Haarala, C., Pesonen, M., et al. (2006). Mobile phone effects on children's event-related oscillatory EEG during an auditory memory task. *Int. J. Radiat. Biol.* 82:443–450.

Krause, C. M., Haarala, C., Sillanmaki, L., et al. (2004). Effects of electromagnetic field emitted by cellular phones on the EEG during an auditory memory task: A double blind replication study. *Bioelectromagnetics* 25:33–40.

Krause, C. M., Pesonen, M., Haarala, C., Hamalainen, H. (2007). Effects of pulsed and continuous wave 902 MHz mobile phone exposure on brain oscillatory activity during cognitive processing. *Bioelectromagnetics* 28:296–308.

Krause, C. M., Sillanmäki, L., Koivisto, M., et al. (2000a). Effects of electromagnetic field emitted by cellular phones on the EEG during a memory task. *Neuroreport* 11:761–764.

Krause, C. M., Sillanmäki, L., Koivisto, M., et al. (2000b). Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. *Int. J. Radiat. Biol.* 76:1659–1667.

LaMotte, R. H., Mountcastle, V. B. (1975). Capacities of humans and monkeys to discriminate vibratory stimuli of different frequency and amplitude: A correlation between neural events and psychological measurements. *J. Neurophysiol.* 38:539–559.

Lashley, K. S., Chow, K. L., Semmes, J. (1951). An examination of the electrical field theory of cerebral integration. *Psychol. Rev.* 58:123–136.

Lebedeva, N. N., Sulimov, A. V., Sulimova, O. P., et al. (2000). Cellular phone electromagnetic field effects on bioelectric activity of human brain. *Crit. Rev. Biomed. Eng.* 28:323–337.

Lebedeva, N. N., Sulimov, A. V., Sulimova, O. P., et al. (2001). Investigation on brain potentials in sleeping humans exposed to the electromagnetic field of mobile phones. *Crit. Rev. Biomed. Eng.* 29:125–133.

Linde, T., Mild, K. H. (1997). Measurement of low frequency magnetic fields from digital cellular telephones. *Bioelectromagnetics* 18:184–186.

Lopes da Silva, F. H. (1999). Event-related potentials: Methodology and quantification. In: Neidermeyer, E., Lopes da Silva, F., eds. *Electroencephalography*. Philadelphia: Lippincott Williams & Wilkins.

Loughran, S. P., Wood, A. W., Barton, J. M., et al. (2005). The effect of electromagnetic fields emitted by mobile phones on human sleep. *Neuroreport* 16:1973–1976.

Maby, E., Le Bouquin Jeannes, R., Faucon, G. (2006). Scalp localization of human auditory cortical activity modified by GSM electromagnetic fields. *Int. J. Radiat. Biol.* 82:465–472.

Maby, E., Le Bouquin Jeannes, R., Faucon, G., et al. (2005). Effects of GSM signals on auditory evoked responses. *Bioelectromagnetics* 26:341–350.

Maby, E., Le Bouquin Jeannes, R., Liégeols-Chauvel, C., et al. (2004). Analysis of auditory evoked potential parameters in the presence of radiofrequency fields using a support vector machines method. *Med. Biol. Eng. Comput.* 42:562–568.

Mann, K., Röschke, J. (1996). Effects of pulsed high-frequency electromagnetic fields on human sleep. *Neuropsychobiology* 33:41–47.

Marino, A. A., Becker, R. O. (1982a). *Electromagnetism & Life*. Albany, NY: State University of New York Press.

Marino, A. A., Becker, R. O. (1982b). *Figure 10.3*, *Electromagnetism & Life*. Albany, NY: State University of New York Press.

Marino, A. A., Nilsen, E., Chesson Jr., A. L., Frilot, C. (2004). Effect of low-frequency magnetic fields on brain electrical activity in human subjects. *Clin. Neurophysiol.* 11:1195–1201.

Marino, A. A., Nilsen, E., Frilot, C. (2003). Nonlinear changes in brain electrical activity due to cell-phone radiation. *Bioelectromagnetics* 24:339–346.

Melville, H. (2004). *Bartleby, the Scrivener*. Whitefish, MT: Kessinger Publishing.

MMF, Mobile Manufacturers Forum. (2008). http://www.mmfai.org/public, Accessed July 29.

OSHA (1990). Electromagnetic Radiation: Field Memo, U.S. Department of Labor, Occupational Safety & Health Administration, Cincinnati, OH. Available at: http://www.osha.gov/SLTC/radiofrequencyradiation/electromagnetic_fieldmemo/electromagnetic.html#Section%206.

Papageorgiou, C. C., Nanou, E. D., Tsiafakis, V. G., et al. (2004). Gender related differences on the EEG during a simulated mobile phone signal. *Neuroreport* 15:2557–2560.

Papageorgiou, C. C., Nanou, E. D., Tsiafakis, V. G., et al. (2006). Acute mobile phone effects on pre-attentive operation. *Neurosci. Lett.* 397:99–103.

Parazzini, M., Brazzale, A. R., Paglialonga, A., et al. (2007). Effects of GSM cellular phones on human hearing: The European project "GUARD". *Radiat. Res.* 168:608–613.

Pederson, G. G. (1997). Amplitude modulated RF fields stemming from a GSM/DCS-1800 phone. *Wireless Netw.* 3:489–498.

Pederson, G. F., Andersen, J. B. (1999). RF and ELF exposure from cellular phone handsets: TDMA and CDMA systems. *Radiat. Protection Dosimetry* 83:131–138.

Perentos, N., Croft, R. J., McKenzie, R. J., et al. (2007). Comparison of the effects of continuous and pulsed mobile phone like RF exposure on the human EEG. *Australas. Phys. Eng. Sci. Med.* 30:274–280.

Perentos, N., Iskra, S., McKenzie, R., Cosic, I. (2006). Characterization of pulsed ELF magnetic fields generated by GSM mobile phone handsets. *IFMBE Proc. World Congr. Med. Phys. Biomed. Eng.* Seoul, Korea, 4:2706–2709.

Regan, D. (1989). *Human Brain Electrophysiology: Evoked Potentials and Evoked Magnetic Fields in Science and Medicine*. Stamford, CT: Appleton & Lange.

Regel, S. J., Gottselig, J. M., Schuderer, J., et al. (2007a). Pulsed radio frequency radiation affects cognitive performance and the waking electroencephalogram. *Neuroreport* 18:803–807.

Regel, S. J., Tinguiely, G., Schuderer, J., et al. (2007b). Pulsed radio-frequency electromagnetic fields: Dose-dependent effects on sleep, the sleep EEG and cognitive performance. *J. Sleep Res.* 16:253–258.

Reiser, H., Dimpfel, W., Schober, F. (1995). The influence of electromagnetic fields on human brain activity. *Eur. J. Med. Res.* 1:27–32.

Röschke, J., Mann, K. (1997). No short-term effects of digital mobile radio telephone on the awake human electroencephalogram. *Bioelectromagnetics* 18:172–176.

Shaw, J. C. (2003). *The Brain's Alpha Rhythms and the Mind*. New York: Elsevier.

Stefanics, G., Kellényi, L., Molnár, F., et al. (2007). Short GSM mobile phone exposure does not alter human auditory brainstem response. *BMC Public Health* 7:325.

Sporns, O., Tononi, G., Edelman, G. M. (2000). Connectivity and complexity: The relationship between neuroanatomy and brain dynamics. *Neural Netw.* 13:909–922.

Terao, Y., Okano, T., Furubayashi, T., et al. (2007). Effects of thirty-minute mobile phone exposure on saccades. *Clin. Neurophysiol.* 118:1545–1556.

Theiler, J., Eubank, S., Longtin, A., et al. (1992). Testing for nonlinearity in a time series; the method of surrogate data. *Physica D* 58:77–94.

Valberg, P. A., van Deventer, T. E., Repacholi, M. H. (2007). Workgroup report: Base stations and wireless networks—radiofrequency (RF) exposures and health consequences. *Environ. Health Persp.* 115:416–424.

Vecchio, F., Babiloni, C., Ferreri, F., et al. (2007). Mobile phone emission modulates inter-hemispheric junctional coupling of EEG alpha rhythms. *Eur. J. Neorusci.* 25:1908–1913.

Wagner, P., Röschke, J., Mann, K., et al. (2000). Human sleep EEG under the influence of pulsed radio frequency electromagnetic fields. *Neuropsychobiology* 42:207–212.

Wagner, P., Röschke, J., Mann, K., et al. (1998). Human sleep under the influence of pulsed radiofrequency electromagnetic fields: A polysomnographic study using standardized conditions. *Bioelectromagnetics* 19:199–202.

Yuasa, K., Arai, N., Okabe, S., et al. (2006). Effects of thirty minutes mobile phone use on the human sensory cortex. *Clin. Neurophysiol.* 117:900–905.