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REVIEW

**THE EFFECTS OF MOBILE-PHONE ELECTROMAGNETIC FIELDS
ON BRAIN ELECTRICAL ACTIVITY:
A CRITICAL ANALYSIS OF THE LITERATURE**

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Abstract

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.

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1. 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 described how the pertinent reports were identified, gave reasons for our treatment of the independent variable, and briefly described the main 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 inquired 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 analyzed the studies globally and explained the basis of our view that the doubt was manufactured by the mobile-phone industry.

2. Methods

2.1. Databases

We searched electronic databases (PubMed, Science Citation Index) using combinations of an electrical term (field, electromagnetic, electric, magnetic, as examples), a device (mobile phone, cellular phone), and an outcome (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 [1].

2.2. 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 μ s, transmitted every 4615 μ s (217-Hz burst rate) at 1-2 watts, delivered from an antenna located near the head [2]. 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) [3-5].

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.

2.3. 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 (Fig. 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.

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 [6]). Presentation of a sensory stimulus as a relatively rare event (for example, 500-Hz tones among more common 1000-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 [6]. 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.

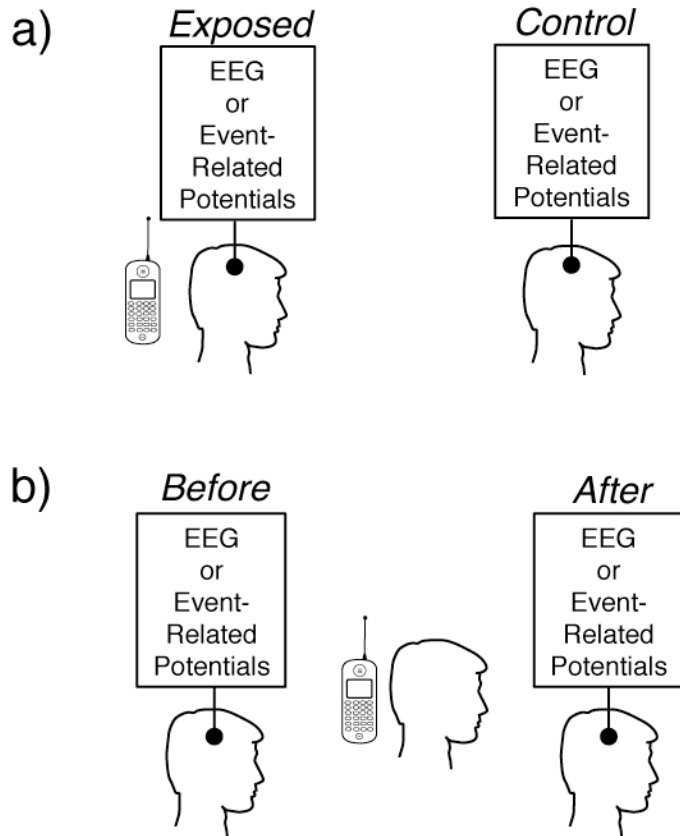


Figure 1. Experimental procedures used to study the effect of mobile-phone electro-magnetic fields on brain electrical activity. a) The electroencephalogram (EEG) was recorded in the presence and absence of mobile-phone EMFs. In experiments where actual mobile phones were used, the EMFs consisted of 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.

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 [6].

3. GSM EMFs and Brain Electrical Activity

3.1. 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 [7]. 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 [8]; 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 $\mu\text{W}/\text{cm}^2$) on the EEG (recorded from C₃ and C₄) in 34 subjects, no effect on spectral power was found during a 3.5-min exposure [9]. Positive controls were not

included; consequently the sensitivity of the experiment for detecting an effect remained unaddressed.

Hietanen et al. [10] 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 x 4 frequency bands x 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. [11] 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. [12] 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, O₁ derivation referenced to O₂). In 12 tests (3 data sets x 4 frequency bands) three 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. [13] described increased spectral power at 9 Hz 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. [14] repeated the study [13] 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. [15, 16] found no effect of mobile-phone EMFs on brain electrical activity, but the studies had too many independent variables (3 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 [17-19]. In the first study [17], the EEG from one derivation was analyzed in 12 subjects on successive nights during the presence (8 hrs) 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 [18] and third [19] 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-hour nighttime sleep session while the subjects were intermittently (15 min on/15 min off) exposed to mobile-phone EMFs [20, 21]; 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 (Fig. 2a) [20]. When the chosen EEG analysis interval was the first 30 min after lights off (the period during which the subjects were falling asleep) [21], there were far fewer pair-wise significant comparisons (Fig. 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 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. [22] 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. [23] 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 [24]. 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 [25] or some other control procedure, which the investigators did not do.

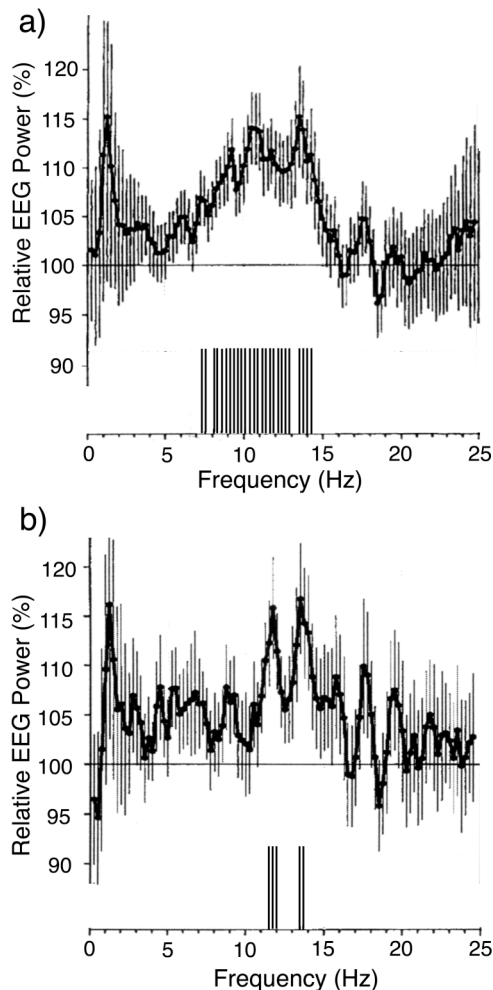


Figure 2. The role of the analysis interval in the decision regarding whether mobile-phone EMFs affected brain spectral power. a) EEG data analyzed for the period between sleep onset and initial REM episode. b) Same data analyzed for the first 30 min period after lights off. The ordinate values are the means (\pm 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. (20) and Huber et al. (21), respectively.

Estonian investigators published five reports dealing with the effect of exposure to pulse-modulated 450-MHz fields on brain electrical activity [26-30]. 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 [30]. 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 [29], 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 [26, 27]. 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 ten 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 [28]; 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 [31, 32, 33]. 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 [31]. Then the investigators computed the temporal and spectral correlation coefficients for some individual subjects, using 13 electrodes [32]. 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 [33].

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 [29] after the results of a prior analysis showed that different subjects responded differently to the fields [28] was particularly inexplicable.

Bak, et al. [34] evaluated the effects of 450, 935, and 1800 MHz mobile-phone EMFs on auditory brain-stem evoked responses measured during and after EMF exposure. Each subject was exposed for 20 minutes, 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. [35] 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 [36] 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 [37], the investigators described bilateral decreases in average slow potentials from a particular collection of derivations (Fig. 4). 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 [38], the investigators used four different averaging intervals none of which were the same as those used in their EMF experiments [37].

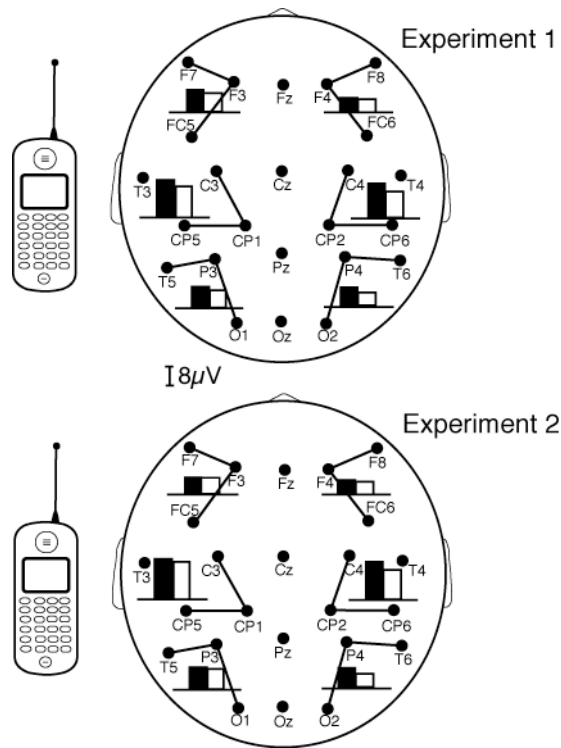


Figure 4. Mean slow potential (time interval -500 to 0 ms from moment of key press) in the visual monitoring task in two independent experiments (from Freude et al. [37]). The lines indicate the electrode derivations that were combined to produce the indicated bar graphs. The data from the other derivations was not used in the analysis.

Hamblin et al. [39] 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 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 [40], 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. [41] 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. [42] 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. [43] 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 1800-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 [44]. 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 [6]. Event-related desynchronization is normally used to study cortical activation, consciousness, and processing of sensory information preparatory to executing a motor command [6]. 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 [45-49]. 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 [48]. However, the result was not replicated in a subsequent study that involved 24 subjects [46]. Desynchronization triggered by a visual memory task was claimed to have occurred in 24 subjects [49]. However, the investigators later revealed that the data had been contaminated by an auditory artifact [45]. They tried again, and claimed to have successfully demonstrated EMF-induced desynchronization in children [45] and adults [47] 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.

3.2. 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 (Fig. 3). The duration of the 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 [7-14, 17-19, 23, 24, 31-41, 45-49], the problem of artifacts was compounded because the magnetic field from the battery current also produces 434 spikes/second. 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 [50]. 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 [7, 11-13, 30]. However sensory stimuli produce both *increases and decreases* in brain alpha, depending on the subject [51]. 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 data.

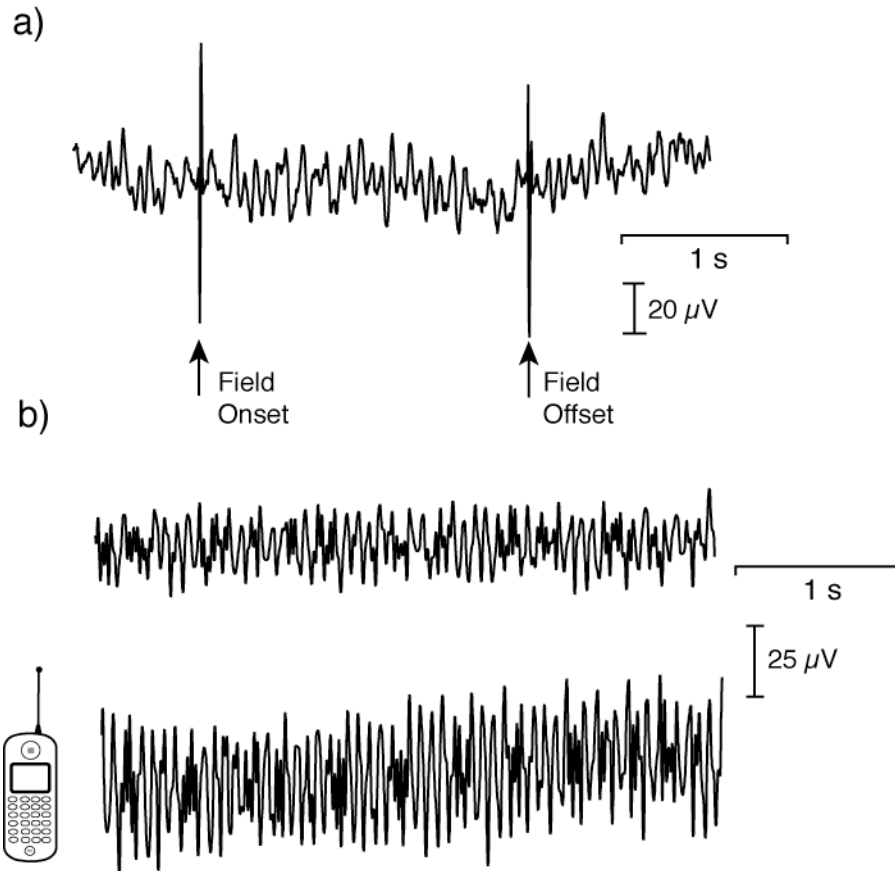


Figure 3. Electrode artifacts created when EEG electrodes are exposed to pulsed electromagnetic fields. a) Electroencephalogram (C_3 , referenced to linked ears) recorded during onset and offset of 2 G, 60 Hz showing the presence of typical spike artifacts (~ 30 ms); the artifacts also occur as a consequence 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).

3.3. *Effects After Exposure*

Vecchio et al. [52] 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. [53] 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. [50] 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 [54-58]. Huber et al. [54] 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. [55] 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. found an after-effect on alpha power in stage two sleep [56]. Regel et al. [57] repeated the study and found an increase in some alpha frequencies in non-REM sleep, but not in stage two sleep.

Hung et al. [58] 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 brain-stem evoked potentials; Stefanics et al. [59] and Parazzini et al. [60] after 10 min exposure, and Arai et al. [61] 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 [62-64]. The exposure did not affect somatosensory evoked potentials [62], the frequency of visual saccades [63], or motor evoked potentials elicited by pulse transcranial magnetic stimulation (a result that was not surprising even to the investigators) [64].

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 [6]. Hinrichs et al. [65] 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.

3.4. *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 [66], 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.

4. Discussion

4.1. *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, as examples) 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 [23, 24, 26, 27], even though it was antithetical to the accepted view of brain function [67-75]. 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 [1, 8, 76-80]. Whether brain electrical activity is also affected by radio-frequency GSM EMFs is an empirical question. Based on results involving older mobile-phone technology [81], a model of a candidate transduction mechanism [82], and empirical observations that the frequency of an EMF is not a primary factor in determining the resulting biological effects [66], we think that properly designed and performed studies likely will reveal that mobile-phone radio-frequency 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 [76, 79]. When the mobile-phone field is terminated, an offset evoked potential occurring 100–400 ms later will also be detected [76]. 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 [78]. 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 [1, 8, 76-80].

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 [36-38, 45-49] or novel dependent variables [43, 44] 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...” [30], “...induced but not evoked brain potential activity...” [35], “...a significant decrease of slow potentials...” [37], “...improve(d) performance...” [41], “...a gender-related influence on brain activity...” [44], “...altered (desynchronization) responses...” [49], “...effects on brain oscillatory responses...” [45], a “(modified)...sleep electroencephalogram...” [55], “...a dose-dependent increase of power...” [57]. 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 (Fig. 3). 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 [31-33]. 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 [34, 59-61], which were all negative and could hardly have been otherwise.

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
42[+]	AstraZeneca Hellas
11[+]	Clarus Products
41[+]	COST281 (F. Funk)
34[-]	EARnEARE (Nokia)
26[+], 27[+],28[+], 29[+], 30[+]	Estonian Science F.
53[+], 54[+], 56[+]	Foundation for R.
35[+]	German R. F .
7[+],9[-],17[+], 18[-], 19[-], 23[+], 24[+], 36[+], 37[+]	German Telekom
43[+], 44[+]	Greek Ministry
59[-], 60[-]	Guard (Nokia)
52[+]	Italian Telecom
65[+]	KPN Mobile
57[+]	Mobile Communication F.
31[+], 32[+], 33[+]	Mobile Communications Consortium
58[+]	Mobile Phone R.
13[+]	Motorola
45[+], 46[-], 48[+], 49[+]	Nokia
22[-]	Radio R.
50[-]	Radiofrequency R. Center
61[-], 62[-], 63[-], 64[-]	Radio-industry & business committee
47[-]	R. Association for Radio Applications
55[+]	R. Council (Nokia)
15[-],16[-],20[+], 21[+]	Swisscom
10[-]	Tech. Dev. Center
12[+], 14[+], 39[+], 40[-]	Telstra R. Laboratories

A fifth problem was that many of the reports violated an important, common-sense 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 [26, 27], or studied the effects of GSM EMFs on phenomena that themselves were not established [43, 44]. 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 [83]. 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.

4.2. 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), we analyzed who authorized the reports. They were all funded, wholly or partially, by the mobile-phone industry (MPI), with only 7 apparent exceptions [26-30, 42, 43].

Did the MPI’s choice of research projects indicate a plan to legitimize its knowledge claims [84-87]? 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 [9, 34, 59, 61]; 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 [83], 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 [84-87], and did so without denying the existence of EMF-induced bioeffects, which was the tactical error made by the

electric power industry thirty 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 [86] 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 [84-87] 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 [7, 11-14, 17, 21, 31-33, 35-37, 39, 45, 48, 49, 53-56, 65]. For example, "The alpha changes...reported in this study have not previously, or in this study, been found to relate to health outcomes" [14]; "Conclusions about possible health consequences are premature, particularly with respect to chronic and/or repeated exposures" [13]; "This study does not allow us to determine any health risks" [35]; "(The results) do not allow any conclusions to be drawn concerning human well-being and health" [37]; "Adverse health effects cannot be derived from these data" [65]; "Conclusions about possible adverse effects on human health are premature because underlying mechanisms are unknown" [54]; "The present results do not allow any conclusions concerning the possible effects of long-term cellular phone use on cognition or health" [45]; "The relevance of our results concerning possible health hazards cannot be assessed yet" [17]; "No statement can be given as to whether a positive or negative influence exists with respect to human health" [7].

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 [88, 89].

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" [90], and that "biological studies must reflect the intricate details of the various (mobile phone) systems" [91]. Consistent with this notion, the reports contained extensive mobile-phone

engineering mumbo-jumbo [10, 15, 21, 46, 60], 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 [92], a long-standing practice has been to use the plane-wave approximation ($E^2/377$) [93] 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 [10, 14-16, 18-22, 31-33, 36, 40, 41, 50, 53-60, 65], 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) unsurprisingly, 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 [81]. 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 [84-87]; 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 [94].

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" [95]. 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 9 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.

4.3. *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* [96]: “We would prefer not to.”

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