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Exposure to ELF Magnetic and ELF-Modulated Radiofrequency Fields: The Time Course of Physiological and Cognitive Effects Observed in Recent Studies (2001–2005)

C.M. Cook,[1]* D.M. Saucier,[1] A.W. Thomas,[2,3] and F.S. Prato[2,3]

[1] *Department of Psychology, University of Saskatchewan,*
Saskatoon, Saskatchewan, Canada
[2] *Department of Nuclear Medicine, Lawson Health Research Institute,*
St. Joseph's Health Care, London, Ontario, Canada
[3] *Department of Medical Biophysics, University of Western Ontario,*
London, Ontario, Canada

In 2002, we published a review of the cognitive and physiological effects of extremely low frequency magnetic fields (ELF MFs) and ELF-modulated radiofrequency fields associated with mobile phones. Since the original preparation of that review, a significant number of studies have been published using techniques such as electroencephalography, event-related potentials and positron emission tomography to investigate electromagnetic field effects upon human physiology and various measures of performance (cognitive, perceptual, behavioral). We review these recent studies, and when effects were observed, we reference the time course of observed effects (immediate or delayed). In our concluding remarks, we discuss a number of variables that are not often considered in human bioelectromagnetics studies, such as personality, individual differences and the specific laterality of ELF MF and mobile phone exposure over the brain. We also consider the sensitivity of various physiological assays and performance measures in the study of biological effects of electromagnetic fields. Bioelectromagnetics 27:613–627, 2006. © 2006 Wiley-Liss, Inc.

Key words: electroencephalography; event-related potential; magnetic fields; cognitive activity; extremely low frequency; radiofrequency; mobile phone

INTRODUCTION

In 2002, we published a review on the cognitive and physiological effects of exposure to extremely low frequency magnetic fields (ELF MFs) and radiofrequency fields (RF) associated with mobile phones [Cook et al., 2002]. Since the publication of that original review, the number of papers examining this subject area has significantly increased, particularly those focusing on the effects of mobile phone exposure upon the human brain. This review provides an update of this research area, covering papers that have been published since 2001. The sections are separated into those studies examining electrophysiological effects of static and ELF MF exposure and those examining the effects of ELF-modulated RF exposure that is associated with mobile phones. Further, each section is categorized into studies involving electroencephalographic (EEG) and event-related potentials (ERPs) studies or those evaluating performance measures due to electromagnetic field (EMF) exposure, including behavioral, cognitive, and perceptual measures. We also provide some background information on the physiological methods and performance measures that were utilized within the reviewed studies.

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*Correspondence to: Dr. C.M. Cook, Department of Psychology, University of Saskatchewan, 9 Campus Drive, Saskatoon, Sask., Canada, S7N 5A5. E-mail: c.cook@usask.ca

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MEASURING PHYSIOLOGICAL EFFECTS IN BIOELECTROMAGNETICS STUDIES

In studies examining the physiological effects of ELF MFs and mobile phone radiation upon the brain, the most common technique used is electroencephalography (EEG). However, recently both magnetoencephalography (MEG) and positron emission tomography (PET) have been implemented as investigative tools. It is far outside the purpose of this discussion to review in detail these specific methods. However, we will briefly touch on the advantages and disadvantages of their usage in bioelectromagnetics studies.

Functional and metabolic imaging of the brain can be performed using a number of methods such as functional magnetic resonance imaging (fMRI, measuring brain blood flow), magnetic resonance spectroscopy (MRS, measuring neurotransmitter concentrations), PET (measuring brain blood flow, metabolism and neuro-receptor occupancy) and single photon emission tomography (SPECT, measuring blood flow and metabolism). To date, only PET has been used to study effects of EMF both during RF exposure and after. Hence these brain-imaging methods could be better utilized to evaluate metabolism and neurotransmitter function. However, if these methods are used to evaluate changes during exposure, some caution in experimental protocol is needed. For example it is well known that SPECT and PET detectors, which use photomultiplier tubes, are sensitive to magnetic fields at a threshold around 100 μT. Hence all such studies of the effects of ELF MFs (e.g., 50 Hz) should confirm using appropriate controls that the SPECT and PET detectors are themselves not affected by the exposure. The same may be true for RF exposures, particularly if associated electronics produce significant ELF components.

An additional potential confounder must be addressed when using magnetic resonance systems (MRI, fMRI, MRS) wherein pulsed ELF or ELF modulated RF is used to probe the brain to obtain the nuclear magnetic resonance signals needed for image formation. It has been shown for some time that these MRI fields can have effects on opioid-related behaviors in rodents [Prato et al., 1987] and most recently, changes in affective behaviors in both rodents and humans [Rohan et al., 2004; Carlezon et al., 2005]. The advantage of these 3-D brain-imaging methods is their high spatial resolution (voxels of mm cube to cm cube in size) throughout the entire brain volume. However, these methods detect comparatively late events, such as blood flow and metabolism, which occur seconds to minutes after the initiation of brain activity. This delay is related to both the limited temporal resolution of the brain imaging methods and also due to a lag in time, after the initial neuronal activity, when the phenomenon to be measured actually occurs. Some studies have sought to overcome the limited temporal resolution of metabolic imaging by combining it with electromagnetic brain mapping for what is termed ''multi-modal'' imaging [Goldman et al., 2002; Oakes et al., 2004].

Electromagnetic brain-mapping methods have been used extensively in the investigation of ELF and RF exposures. These methods, as compared to the brain imaging methods, are entirely passive and hence can be more easily applied to volunteers, that is, there is no ionizing radiation and no strong magnetic fields. Interestingly, these methods have poorer spatial resolution than the imaging methods but superior temporal resolution (i.e., milliseconds). The main technique used is EEG which measures brain electrical activity. Depending on the number of channels used, sources of EEG signal can at best be estimated to within a few centimeters. State-of-the-art EEG systems now employing large number of electrodes (>256 channels) have improved the spatial resolution of the cerebral cortex, but signals from deeper structures remain difficult to detect reliably. Interference by applied ELF and RF fields are also a problem for EEG work. The EEG electrodes and leads can act as antennas that can (a) inject current into the subject's scalp and (b) induce potentials on the EEG leads which have significantly greater amplitude than the brain signals being measured. Hence reliable measurements during exposures are almost impossible. Interestingly at least one group has made reliable measurements ''during'' exposure by modifying the EEG detection circuit to ground out the leads during induced voltages and then making measurements between pulses separated by a few hundreds of milliseconds [Cook et al., 2005].

The magnetoencephalogram (MEG) can also be used to map the brain electromagnetic activity, in this case the magnetic activity. MEG offers better spatial resolution than EEG with comparable temporal resolution. The main disadvantage of MEG is that the brain magnetic field activity is very weak (order of fT) compared to ambient field conditions (order of 0.1 mT). Hence MEG is extremely sensitive to external noise, which requires the unit to be contained within an extensive magnetic shielded environment. Consequently, at least to date, MEG cannot be used for real time assessment of EMF effects as the applied signal interferes so strongly with the measurement that the exposure needs to be carried out remotely from the MEG facility, that is, on the outside of the shielded room.

MEASURING PERFORMANCE IN BIOELECTROMAGNETIC STUDIES

Assessing the effects of EMFs upon perception, cognition and behavior is typically measured through the administration of a performance task. The majority of bioelectromagnetics studies examine how EMFs affect cognitive constructs such as ‘‘attention’’ and ‘‘working memory.’’ As these abilities are considered of great importance in an individual’s day-to-day life, their choice as a common dependent variable is one index of EMFs as a potential health hazard. Any stimulus that interferes with such abilities must be seriously considered.

Working memory and attention are two very large psychological constructs. As such, there are numerous tasks researchers may employ to assess how EMFs may affect them. Working memory is best described as the ability to maintain and manipulate data over a short time-period, usually on the order of a few seconds [Baddeley, 1992]. An example of a working memory task is the ‘‘n-back’’ paradigm. This is a four-condition test, wherein subjects are required to continuously monitor a series of stimuli (e.g., in the visual domain, letters), while keeping track of targets that previously occurred in the sequence (the one previous to the target, that is, 1-back, 2-back, and 3-back). This task increases in difficulty, with a 3-back task presenting a significant challenge to an individual’s ability to hold several items within the working memory space.

Measuring ‘‘attention’’ in an individual is even more complicated. Attention is not a unitary factor, and attempts to assess this construct should address the multifaceted aspects of attention. Measurements of attention range from simple reaction time to more complicated paradigms of divided, sustained, and focused attention. The interplay between attentive processing and working memory obviously overlaps to significant degree. For instance, how fast the attention system operates and how much it can process at once are different facets of the same construct. Depending on the theoretical bias of the researcher, many of these tests have been considered tests of attentional capacity by one group and working memory ability by others [Lezak, 1995].

In the sections on the effects on performance measures, the reader may wish to consult Table 1 to clarify the purpose of the task and the ability it is designed to assess.

STATIC AND EXTREMELY LOW FREQUENCY MAGNETIC FIELD EFFECTS

Studies Involving Electroencephalography and Event-Related Potentials: Time Course of Observed Effects

Effects from static and extremely low frequency fields may elicit their maximal response over longer time scales than may typically be studied. Post-exposure, maximal effects on EEG and ERPs may occur over periods ranging in duration from minutes to hours [e.g., Fuller et al., 2003; Cook et al., 2004]. This position is far from universally supported, as many studies do not investigate effects over a long enough post-exposure duration [Marino et al., 2004; Ghione et al., 2005] and at least one study has failed to observe significant effects [e.g., Cook et al., 2005] during this period. An overview of the results of these studies can be found in Table 2.

Immediate effects. Marino et al. [2004], using a technique from nonlinear dynamics called percent recurrence (*%R*, a measure of how much a signal correlates with itself in phase space), investigated intra-subject EEG responses during exposure to a 60 Hz, 100 μT MF. They found that eight out of eight subjects detected the MF as evidenced by significant changes in %R calculated from at least two electrodes (C3, C4 central; P3, P4, parietal; O1, O2, occipital) in each subject. Ghione et al. [2005] used a 50 Hz MF at two intensities 40 or 80 μT_{pk} to examine effects upon EEG alpha (8–13 Hz) activity, pain perception and cardiovascular variables (heart rate (HR) and blood pressure) in 40 subjects. Over the course of a 90 min exposure, they reported significantly lower pain thresholds in subjects exposed to the 50 Hz 40 μT_{pk} MF, compared to sham. They also found that EEG alpha activity was significantly increased, but only in subjects exposed to the 50 Hz, 80 μT_{pk} MF compared to sham. Again, these effects were observed immediately following exposure, and do not speak to potential effects at longer durations.

Delayed effects. Consistent with their previous work [Fuller et al., 1995; Dobson et al., 2000a,b], Fuller et al. [2003] observed that the application of a 2000 μT DC and very low frequency MF (0–0.02 Hz) increased the interictal firing rates of three epileptic patients who had depth electrodes implanted in their hippocampal formation. Following exposure these effects became *more* pronounced over time scales of minutes to an hour, as compared to the first 10 s after the field is turned off. Similarly, Cook et al. [2004] found higher EEG occipital alpha activity (8–13 Hz) following a 15 min exposure to a pulsed 200 μT_{pk} ELF MF in 20 subjects. Significant effects were also noted nearly 10 min into the post-exposure period. In a follow-up study on another 20 subjects [Cook et al., 2005], it was found that once again occipital alpha activity in the EEG was affected by the pulsed ELF MF, but significantly *decreased* during the first 5 min of the exposure period. However, the significant EEG alpha increase found in

TABLE 1. Outline of Performance Measures Used in Reviewed Studies

Ability	Task	Description	Used in
Working memory	n-back paradigm; visual/spatial working memory; short term recall; immediate word recognition; picture recognition; recognition memory; Brown-Peterson; perceptual priming	Assesses the ability of keeping an amount of information "in mind" in the short-term period (minutes) and identify or relay back that information if required	Lass et al. [2002]; Podd et al. [2002]; Smythe and Costall [2003]; Delhez et al. [2004]; Haarala et al. [2003b, 2004, 2005]; Besset et al. [2005]; Preece et al. [2005]
Long-term memory	Long-term recall; delayed word/picture recognition	Requires the generation of learned information at a much later time period >10 min onwards	Smythe and Costall [2003]; Preece et al. [2005]
Attention, working memory	Forward and backward digit/spatial span; time estimation; visual and auditory discrimination; Benton visual retention test; auditory-verbal learning	Highlights need of subject to closely concentrate on a task while also requiring the need to keep information "in mind" simultaneously	Edelstyn and Oldershaw [2002]; Podd et al. [2002]; Kurokawa et al. [2003]; Haarala et al. [2003a]; Delhez et al. [2004]; Maier et al. [2004]; Besset et al. [2005]
Attention, motor speed	Simple/choice/10 choice reaction time; trail making test; flexibility task; figure cancellation	Requires concentration on a target stimulus with emphasis on reaction speed to the target	Lass et al. [2002]; Kurokawa et al. [2003]; Lee et al. [2003]; Curcio et al. [2004]; Delhez et al. [2004]; Besset et al. [2005]; Haarala et al. [2005]; Preece et al. [2005]
Attention, focused and sustained	Sustained attention to response; verification vigilance; Stroop test; symbol digit; visual search; dual/divided attention; digit vigilance	Highlighted by intense concentration for an extended period on a single entity with competing stimuli or distractions	Lass et al. [2002]; Haarala et al. [2003a, 2005]; Lee et al. [2003]; Curcio et al. [2004]; Delhez et al. [2004]; Besset et al. [2005]; Preece et al. [2005]
Executive function	Verbal fluency; serial subtraction	Tasks require the spontaneous generation of words or solutions to calculations	Edelstyn and Oldershaw [2002]; Haarala et al. [2003a]; Curcio et al. [2004]
Motor dexterity	Purdue pegboard	Timed placement of pegs with right, left and both hands	Besset et al. [2005]
Visual perception	Figure perception test	Judgment of length line differences in a visual Illusion (Müller-Lyer)	Kurokawa et al. [2003]

TABLE 2. Summary of Static and ELF Magnetic Field Effects Upon the Electroencephalogram (EEG) and Event-Related Potentials

Study	Parameters	Effects
Fuller et al. [2003]	2000 μT <60 min	↑ epileptiform activity (medial temporal lobe)
Marino et al. [2004]	60 Hz 100 μT; 2 s exposure	↑ % recurrence over occipital, parietal, central regions
Cook et al. [2004]	Pulsed ELF 200 $\mu T_{pk\text{-}pk}$; 15 min	↑ occipital alpha activity (8–13 Hz)
Cook et al. [2005]	Pulsed ELF 200 $\mu T_{pk\text{-}pk}$; 15 min	↓ alpha activity in first 5 min of MF exposure
Crasson and Legros [2005]	50 Hz, 100 $\mu T_{rms;}$ 30 min	No effect
Ghione et al. [2005]	50 Hz 40 and 80 μT_{pk}; 15 min	↑ occipital alpha activity (8–13 Hz)

The ↑ and ↓ indicate whether EEG activity was found to have increased or decreased due to magnetic field exposure. Exposure parameters are summarized if provided.

Cook et al. [2004] was not found in the follow up study, which may relate to the modification of the pulsed ELF MF design in the latter study. However, individual differences may also play an important role in the EEG alpha response to ELF MFs [Shaw, 2003].

No effects. Conversely, Crasson and Legros [2005] attempted to replicate and extend their previous work [Crasson et al., 1999] using a 50 Hz 100 μT_{rms} MF continuously presented for 30 min compared to a sham exposure and a visible light exposure [$n = 18$]. Several measures were examined, some of which were performed during the exposure, including subjective (visual analogue scale, state-trait anxiety) and cognitive tasks of attention (duration-discrimination, Stroop Colour Word) tasks. In addition to EEG, performance on a dichotic listening task and visual ERPs were assessed after the exposure period. Although no significant effects were found for any of the measures in Crasson and Legros [2005], the authors acknowledge that this may be due to the difference in MF presentation between the current study and their previous work [Crasson et al., 1999]. For instance, the 2005 study used a continuous presentation of the MF, whereas the 1999 study used an intermittent presentation. Finally, it should be stressed that this post-exposure technique typically examines these effects within seconds of exposure. In Crasson and Legros [2005], electrode placement for the EEG measures was performed immediately post-exposure. As such, it is possible that significant effects were missed during the preparation for the electrophysiology portion of the experiment.

Studies Involving Performance Measures: Time Course of Effects

As was the case with EEG and ERP studies, performance effects from static and ELF MFs may have their maximal effects over longer time scales than typically measured. Effects have been noted immediately during the exposure period [Shupak et al., 2004a], and following a delay [Podd et al., 2002]. Others have failed to find any effects [Kurokawa et al., 2003; Delhez et al., 2004]. Most of these studies, with the exception of Podd et al. [2002], do not investigate effects over a longer post-exposure duration. An overview of the results of these studies can be found in Table 3.

Immediate effects. Over the course of two experiments ($n = 34$ and $n = 31$) Shupak et al. [2004a] exposed subjects to a pulsed 200 μT_{pk} ELF MF for 30 min to assess the effects upon sensory and pain thresholds. Subjects' thresholds were tested in the pre-exposure period and immediately in the post-exposure period. It was found that pulsed MF exposure increased subjective pain thresholds after the MF exposure, but not the sham exposure. This result is consistent with their previous pulsed MF results with an animal model [Thomas et al., 1997a,b; Shupak et al., 2004b].

Delayed effects. Attempting to replicate the Whittington et al. [1996] study, Podd et al. [2002] used the same visual duration discrimination task to assess the effects of a 50 Hz 100 μT MF exposure (1 s on, 1 s off) in 80 subjects. Although they were unable to replicate the reaction time effect found in Whittington et al. [1996], they did find a significant decrease in recognition memory performance in subjects exposed to the MF. Interestingly, this was a delayed effect, occurring several minutes after the exposure period. Subjects were exposed to the MF during the discrimination portion of the visual task. After competing that measure (<15 min MF exposure), subjects were then tested on visual recognition, which was found to be significantly affected by MF exposure.

No effects. Kurokawa et al. [2003] used a battery of sensory and perceptual tasks (simple reaction time, choice reaction time, time perception, figure perception test) to assess the effects of a continuously presented 50 Hz, 20 μT_{rms} MF on 20 subjects for 55 min. MF exposure took place while subjects were performing the different tasks. No changes in performance were noted in any of the reaction time or time perception tasks due to MF exposure. Delhez et al. [2004] investigated the cognitive effects in 32 volunteers of 20 and 400 μT 50 Hz MFs, continuously presented in a double-blind crossover design for 65 min. Subjects were exposed to

TABLE 3. Summary of Static and ELF Magnetic Field Effects Upon Performance Measures

Study	Parameters	Task	Effect on Performance
Podd et al. [2002]	50 Hz, 100 μT	Visual discrimination	No effect
		Recognition memory	↓ in performance (delayed)
Kurokawa et al. [2003]	50 Hz, 20 μT_{rms}; 55 min	Simple reaction time, choice reaction time, time perception, figure perception test	No effect
Delhez et al. [2004]	50 Hz; 20 and 400 μT; 65 min	Brown–Peterson working memory task, digit span, digit span with articulatory suppression, working memory task, flexibility task, divided attention, time reproduction	No effect
Shupak et al. [2004a]	Pulsed ELF MF; 200 μT	Pain thresholds	↑ subjective pain thresholds
Ghione et al. [2005]	50 Hz 40 and 80 μT_{pk}; 15 min	Pain thresholds	↓ subjective pain thresholds

The ↑ and ↓ indicate whether performance on cognitive or perceptual tasks was affected due to magnetic field exposure. Exposure parameters are summarized if provided.

the MF during their performance of the various tasks to assess any immediate effects. Using a number of tests of working memory and attention (Digit Span, Brown–Peterson, Flexibility task, working memory, flexibility, divided attention and time reproduction), they found no effect of either field intensity on any of the tasks.

ELF-MODULATED RADIOFREQUENCY EXPOSURE

Studies Involving Electroencephalography and Event-Related Potentials: Time Course of Observed Effects

Like the studies reported in the previous sections on ELF exposure, there is some indication that exposure to radiofrequency and ELF MFs associated with mobile phones may exert effects after the cessation of the actual exposure. This observation, although not universally reported, is noted over several electrophysiological studies [Huber et al., 2002, 2003, 2005; Hamblin et al., 2004; Hinrichs and Heinze, 2004; Curcio et al., 2005]. Immediate effects of mobile phone exposure were seen in several studies [Croft et al., 2002; D'Costa et al., 2003; Krause et al., 2004; Papageorgiou et al., 2004]. Interestingly, no EEG or ERP studies reported null effects. An overview of the results of these studies can be found in Table 4.

Immediate effects. Croft et al. [2002] used a standard Nokia mobile phone (900 MHz, 217 Hz pulse rate, 577 µs pulse width; average power 3–4 mW) to assess subjects' ($n = 20$) resting EEG and performance on an auditory discrimination task. Mobile phone exposure was found to significantly increase alpha activity (8–12 Hz), while significantly decreasing the delta (1–4 Hz) activity over the right hemisphere. The earlier theta (4–7 Hz) and beta (12–30 Hz) components were found to be reduced during the auditory discrimination task. No effect of the EMF was found on the task performance. D'Costa et al. [2003] examined the EEG from ten subjects taken during exposure to the EMF from a GSM mobile phone (900 MHz, modulated at 217 Hz, average power 250 mW) in a single blind study. Ten subjects were exposed over the midline cortical region in 5 min intervals to a randomized, interrupted sequence of five active and five sham exposures, with average EEG band power in active exposure compared to sham recordings. Significantly higher alpha (8–13 Hz) and beta (13–32 Hz) activity was found in the active exposed condition compared to sham over the central and occipital regions.

Papageorgiou et al. [2004] assessed EEG changes during a memory test in response to a 900 MHz EMF (mean power 64 mW). Nineteen subjects were randomly exposed to both sham and exposure conditions (right hemisphere only) both of which were

TABLE 4. Summary of ELF Modulated RF Field Effects Upon the EEG and Event-Related Potentials

Study	Parameters	Effects
Croft et al. [2002]	900 MHz (217 Hz); <60 min midline exposure	↑ alpha activity (8–12 Hz); ↓ delta activity (1–4 Hz); ↓ in theta (4–8 Hz) and beta (12–30 Hz) during discrimination task
Huber et al. [2002]	900 MHz (217 Hz); 30 min LH exposure	↑ alpha activity (8–13 Hz)
Huber et al. [2002]	900 MHz (217 Hz); 30 min LH exposure	↑ rCBF over the dorsolateral frontal (Brodmann areas 6, 9, 10, 44), parietal (Brodmann areas 2, 40) and ↓ rCBF over the right posterior cerebellum
Huber et al. [2003]	900 MHz (2, 8, 217 Hz); 15 min LH and RH exposure	↑ alpha activity (9–14 Hz)
D'Costa et al. [2003]	900 MHz (217 Hz); midline exposure	↑ alpha activity (8–13 Hz); ↑ beta activity (13–32 Hz)
Hamblin et al. [2004]	894.6 MHz (217 Hz); RH exposure	↓ N100 amplitude; ↓ N100 and P300 latencies over midline electrodes
Hinrichs and Heinze [2004]	1800 MHz (217 Hz); 30 min LH exposure	↓ in event related magnetic fields amplitude in 300–500 ms time window
Krause et al. [2004]	902 MHz (217 Hz); 30 min LH exposure	↓ in event related synchronization of theta activity (4–7 Hz)
Papageorgiou et al. [2004]	900 MHz, (217 Hz); 45 min RH exposure	↓ overall EEG energy in male subjects; ↑ overall EEG energy in female subjects
Curcio et al. [2005]	902.4 MHz (217 Hz); 45 min LH exposure	↑ central and parietal alpha activity (8–13 Hz)
Huber et al. [2005]	900 MHz, (217 Hz); 30 min LH exposure	↑ rCBF over the dorsolateral frontal (Brodmann areas 6, 9, 10, 44), parietal (Brodmann areas 2, 40) ↓ rCBF over the right posterior cerebellum
Loughran et al. [2005]	894.6 MHz (217 Hz); 30 min RH exposure	↑ central alpha activity (8–13 Hz)

The ↑ and ↓ indicate whether the evoked potential waveform was found to increase or decrease due to magnetic field exposure. Exposure parameters are summarized and laterality of exposure described (right hemisphere, RH; left hemisphere, LH).

45 min duration, separated by approximately 2 weeks. A significant difference was found between male and female subjects in terms of exposure. In the baseline period, male subjects displayed greater EEG energy than female subjects. This observation was reversed during the exposure period, whereby male subjects displayed significantly decreased EEG energy during the EMF and female subjects displayed significantly increased EEG energy. There were no performance differences between males and females on the accompanying memory task.

Krause et al. [2004] attempted to replicate an earlier work [Krause et al., 2000a], investigating the effects of EMF (GSM, 902 MHz, 217 pulse modulation, pulse width 577 µs, mean power 0.25 W) on EEG responses during a memory task in 24 subjects. The 2004 study was double blinded and exposure was to the left hemisphere, as compared to the 2000 study which exposed the right side of the head only. They found that event-related synchronization (ERS) responses for the 4–6 Hz band (covering high delta/low theta activity) were reduced in magnitude during EMF exposure. They also found that EMF exposure decreased the ERS within the high theta/low alpha frequency (6–8 Hz) during memory retrieval over the left hemisphere. This latter result was the only consistent finding with their previous work [Krause et al., 2000a]. They also found that EMF exposure significantly increased the number of incorrect answers, a finding not noted in Krause et al. [2000a].

Delayed effects. Huber et al. [2002] presented a two-part study to assess EEG during sleep ($n = 16$) and, for the first time in a bioelectromagnetics experiment, regional cerebral blood flow (rCBF) using PET ($n = 16$). In both studies, a pulse modulated (pm) EMF, applied to the left hemisphere only, was used. The features of this pm-EMF were similar to the spectral content of a GSM mobile phone (900 MHz, 2, 8, 217, 1736 Hz modulation). In the sleep study, in addition to the pm-EMF, a continuous wave (cw)-EMF was also used to assess how EMF exposure during the waking state affects a subsequent sleep episode in 16 male subjects. Following a 30 min exposure to pm-EMF, alpha activity (8–13 Hz) significantly increased. This trend continued into the sleep period, increasing alpha activity (sleep spindles) in the EMF condition, relative to sham. This enhancement of alpha activity was not noted in the cw-EMF exposure. In the PET portion of the experiment, it was found that pm-EMF increased rCBF in the dorsolateral left frontal region. Interestingly, there was a 10 min period between EMF exposure and the PET scan, suggesting that cessation of the EMF does not necessarily immediately halt physiological effects.

In two experiments, Huber et al. [2003] re-examined the effects of a bilateral exposure to a radiofrequency (RF) EMF (900 MHz with various ELF modulation frequencies, 2, 8, 217, 1733 Hz and 50 kHz; two different specific absorption rates) on EEG, cardiovascular and sleep variables. In experiment 1, 24 male subjects were intermittently exposed (every 15 min) to an EMF (whole head SAR) during a nighttime sleep episode to assess EEG and HR. In experiment 2, 16 male subjects were exposed to an EMF (unilateral SAR) for 30 min prior to a 3 h daytime sleep episode also assessing EEG and HR. In both experiments there was a significant increase in alpha activity (9–14 Hz) after RF-EMF, irrespective of exposure type (whole head vs. unilateral exposure) or duration (15 min intermittently presented during the night vs. 30 min waking exposure prior to sleep). In the first experiment, subjects also displayed a reduction in waking after sleep onset (WASO), which most interestingly, was order specific, that is, subjects who were sham exposed first exhibited larger decreases in WASO compared to subjects who were field exposed first.

Hamblin et al. [2004] examined the effect of an 894.6 MHz (pulse modulation 217 Hz, width 566 µs, power output 250 mW) mobile phone on sensory processing using an auditory evoked potential (EP) in an oddball task with exposure over the right hemisphere only ($n = 12$). It was found that auditory EP amplitude at N100 was reduced and the N100 and P300 waves were delayed in response to non-targets in the EMF exposure relative to sham. These effects were largest over the midline and right hemisphere regions. They found no effect of the mobile phone on reaction times. This study also suggests there may be delayed effects of exposure, as EMFs were turned on during the practice trials and stayed on continually until the beginning of the test trials 30 min later, for a total EMF exposure of 1 h.

In a unique experiment, Hinrichs and Heinze [2004] investigated the effects of a GSM 1800 MHz EMF (pulsed at 217 Hz, average power 0.125 W) on verbal memory encoding as measured by MEG. To reduce the severe artifacts that would have been introduced by the EMF, active and sham exposures took place during the encoding portion of the memory task. Twelve subjects were exposed to either EMF (left hemisphere only) or sham for 30 min. After this exposure period, the effects of EMF on the MEG signal were examined while subjects attempted to retrieve the items from memory that they learned during the initial exposure. EMF exposure was found to induce a task-specific alteration of left hemisphere MEG waveforms over temporo-occipital regions, in the 300–500 ms time window (roughly corresponding to the P300 time window in EEG). The authors note that they cannot positively ascertain whether the effects found are specific to the retrieval process or simply a delayed effect of the EMF exposure that occurred during the earlier exposure period. No effect was found for the behavioral data between EMF and sham conditions. However, any interpretation of these results should also consider the recent observations that Mu-metal shielding affects mouse nociception [Choleris et al., 2002; Prato et al., 2005]. This type of shielding is also utilized in MEG studies to remove environmental noise, such as stray ELF magnetic fields. As such, it is possible that basic shielding of ELF magnetic fields may also induce effects in human volunteers.

Curcio et al. [2005] examined how the resting EEG is affected by a GSM signal (902.4 MHz, pulse modulation 217 Hz, average power 0.25 W). Twenty subjects were assigned to one of two groups experiencing three conditions presented in random order (baseline, EMF, and sham exposure). Group 1 received the EMF signal for 45 min (over the left hemisphere) *before* the EEG recording and the other group were exposed for the same exposure length, but EEG was recorded during the last 7 min of exposure. To reduce the possibility that auditory signals may be given off by the mobile phone, subjects were exposed to white noise to create a uniform auditory environment. They found that the GSM signal affected a small frequency band, specifically increasing the alpha band (8–13 Hz), an observation consistent with other mobile phone experiments [Huber et al., 2000, 2002, 2003; Krause et al., 2000a,b; Lebedeva et al., 2001; Croft et al., 2002; D'Costa et al., 2003]. Although this study also supports the position that delayed effects to mobile phone exposure may occur, there was also a significant immediate increase in a single frequency bin (11 Hz) in subjects exposed to EMF.

In a follow-up to their previous 2002 study, Huber et al. [2005] examined rCBF, (as measured by PET) in response to a ''base-station like'' RF signal (mimicking the signal given off by a GSM base station) and a ''handset like'' RF signal (similar to that given off by GSM phones). Sixteen subjects were exposed (left hemisphere only) to the same RF signal and apparatus as Huber et al. [2000, 2002] for 30 min prior to undergoing a PET scan. After a 10 min delay between the end of exposure and the scan, it was found that once again EMF affected rCBF in the left hemisphere (the exposed side). The handset RF signal had the most significant effects compared to the base-station signal or sham, tending to increase rCBF over the dorsolateral frontal (Brodmann areas 6, 9, 10, 44) and parietal (Brodmann areas 2, 40) regions, but decreasing rCBF over the right posterior cerebellum. This study is quite interesting in that it demonstrates the importance of the pulse modulation scheme in eliciting biological effects of RF signals. The ''hand-set'' and the ''base-station'' signals both had the same time-averaged energy, but the handset signal had higher power in the main spectral components, which were in the ELF range (2, 8, 217, 1736 and harmonics).

Attempting to replicate Huber et al. [2002, 2003], Loughran et al. [2005] exposed 50 participants to a mobile phone over right hemisphere only (temporal lobe region) for 30 min before a nocturnal sleep episode. The GSM mobile phone was a modified Nokia 6110 and had a 894.6 MHz RF pulsed at 217 Hz (duty cycle 12.5 Hz, pulse width 0.576 µs, peak SAR 0.29 W/kg) set to continuously transmit at 2 W (mean power output 0.25 W). A 30 min EMF exposure decreased REM sleep latency and increased EEG activity in a narrow frequency band, 11.25–12.5 Hz, corresponding to the alpha frequency band. Most interesting was the analysis of the temporal evolution of the EEG changes, which indicated the enhancement was not evident until 10 min into the first non-REM period. This further suggests that a brief EMF exposure during the waking period can affect subsequent EEG sleep activity and supports the Huber et al. [2002, 2003] observations.

Performance Measures: Time Course of Effects

Compared with the studies examining EEG and ERP responses to mobile phone exposure, there seem to be fewer studies reporting significant effects upon performance measures. Significant results tended to be found immediately following exposure [Lass et al., 2002; Lee et al., 2003; Smythe and Costall, 2003; Maier et al., 2004]. However, there are considerably more null outcomes [Haarala et al., 2003a,b, 2004, 2005; Besset et al., 2005; Preece et al., 2005] compared to the electrophysiological studies. Only two experiments noted delayed effects of mobile phone exposure [Edelstyn and Oldershaw, 2002; Curcio et al., 2004]. As these performance measures were typically carried out immediately during the exposure period to assess acute effects of mobile phone exposure, it is possible that significant responses have been missed as effects may have occurred in the post-exposure ''wash-out'' period.

Immediate effects. Lass et al. [2002] randomly assigned 100 subjects (37 female; 63 male) to a 450 MHz EMF (SAR, 0.0095 W/kg) amplitude modulated at 7 Hz (50% duty cycle) exposure group

($n = 50$) or a sham group ($n = 50$). Exposure was for 10–20 min (right hemisphere exposure) during which the subjects performed a number of neuropsychological tests (trail making test, visual short term memory, symbol digit modalities). There was a significant difference in variance between the exposed and sham groups in their most complex task (Task 1, a modified trail making test requiring short-term memory and divided attention). There was a tendency for the EMF exposed group to make more errors. The authors concluded that the application of an external stressor, that is, EMF exposure, likely added to the larger variability in scores in the exposed group. They also note that the effect varied widely among subjects.

Lee et al. [2003] randomly assigned 78 students to either an EMF exposure or to a control group. EMF exposure consisted of a 1900 MHz GSM mobile phone (Nokia 3210) over the right hemisphere. Subjects' performance was assessed with various neuropsychological tests, including the trail making test (as in Lass et al., 2002) and the sustained attention to response test. It was found that reaction time in the sustained attention test decreased (performance was increased) over the experimental time in the EMF-exposed group compared to control, which is consistent with Koivisto et al. [2000a] and Preece et al. [1999]. Smythe and Costall [2003] examined short- and long-term memory performance in 62 subjects (33 males; 29 females) who were randomly assigned to one of three test conditions (no phone, inactive phone, and active phone). Subjects in the inactive phone and active phone exposure conditions had the phone positioned over the left hemisphere. The 15 min EMF exposure was at 1800 MHz with a SAR of 0.79 W/kg. There were no short-term memory differences among any of the three groups. However, when male subjects were exposed to the active EMF condition, there were significantly lower error rates (fewer spatial and semantic errors) than when they were exposed to the inactive condition. This is one of the first studies to demonstrate a sex-specific effect for EMF exposures.

Maier et al. [2004] tested 11 subjects' performance on an auditory discrimination task known as order threshold (OT). This task requires subjects to determine whether two successive stimuli were separate and on which side the stimuli were presented. Subjects performed baseline measurements followed by a relaxation phase for 50 min during which EMF was either on or off. Performance on the OT task was significantly impaired in 9 out of 11 subjects following a 50 min exposure to a 902 MHz EMF (pulse modulated at 217 Hz, left hemisphere only) compared to the control condition.

Delayed effects. Edelstyn and Oldershaw [2002] investigated the effects of a 30 min 900 MHz mobile phone (SAR, 1.19/kg of exposed body tissue) exposure (left hemisphere only) in 38 normal subjects. Before, during and after exposure, a number of neuropsychological tasks of attention and processing speed were performed (digit span backwards/forwards, spatial span backwards, serial subtraction, and verbal fluency). Subjects demonstrated improved immediate verbal and visuospatial working memory capacity and sustained attention (forward/backward digit span and serial subtraction tasks), with the significant effects noted 15 min after the 30 min exposure to the mobile phone. When neuropsychological testing occurred 30 min post-exposure, no significant effects were found. Curcio et al. [2004] assigned 20 subjects to two groups, one receiving EMF exposure over the left hemisphere (902.4 MHz, average power 0.25 W) for 45 min before the experimental session and the other exposed for 45 min during the experimental session to examine performance on a number of neuropsychological tests (reaction time, arithmetic subtraction, visual search, acoustic choice reaction time). Every subject had a baseline, sham (EMF-off) and an exposure condition (EMF-on), counterbalanced in a double-blinded fashion. They found that subjects exposed to the EMF condition again displayed faster reaction times. However, subjects pre-exposed to mobile phones 45 min before testing displayed significantly faster reaction times than those subjects exposed during the testing period. There were no significant effects upon subjects' accuracy on the tasks. These authors also call for increased examination of the EMF ''washout'' or post-exposure period where, they suggest, a number of effects may go undetected.

No effects. Haarala et al. [2003a] attempted to replicate their earlier study [Koivisto et al., 2000a], using the same mobile phone parameters (GSM, 902 MHz, 217 pulse modulation, pulse width 577 μs, 0.25 W; left hemisphere exposure) and cognitive tasks (simple reaction time, choice reaction time, 10 choice reaction time, subtraction task, verification, and vigilance tasks). Improvements were made in the methodology with a larger sample size (64 subjects overall), multi-centered sampling ($n = 32$ in Finland; $n = 32$ in Sweden), more tests and a double-blind condition. The previous results of Koivisto et al. [2000a] were not confirmed, as no significant effects were found. Another study by Haarala et al. [2003b] extended their previous work by exposing 14 subjects to a GSM type mobile phone (GSM, 902 MHz, 217 pulse modulation, pulse width 577 μs, mean power 0.25 W; left hemisphere exposure) and performing the n-back working memory task while undergoing a PET scan to assess rCBF changes (using a ^{15}[O]water bolus). While Huber et al. [2002] were the first to utilize PET to assess EMF effects, they examined subjects after the exposure period. Haarala et al. [2003b] were the first to examine the effects of mobile phone exposure on rCBF during a mobile phone exposure. They found that EMF exposure reduced bilateral rCBF in the temporal lobes (predominantly left hemisphere), but had no effect on the working memory task. The authors suggest that the deactivation associated with EMF exposure may be due to the visual task requirements or a non-conscious perception of a high frequency auditory signal given off by the mobile phone.

In an attempt to replicate Koivisto et al.'s [2000b] finding of facilitatory EMF effects upon short term memory, Haarala et al. [2004] exposed subjects (left hemisphere only) to the same exposure conditions (GSM, 902 MHz, 217 pulse modulation, pulse width 577 μs, mean power 0.25 W) and used a slightly modified version of the n-back working memory task. They also attempted to improve the methodology by increasing sample size ($n = 64$, in a multi-centered study, $n = 32$ Finland, and $n = 32$ Sweden) and implementing a double-blind design. In a 65 min exposure period, they found, like the Haarala et al. [2003a] attempt at replication, they were unable to repeat the results of Koivisto et al. [2000b].

Haarala et al. [2005] investigated the neuropsychological effects of a mobile phone (GSM, 902 MHz, 217 pulse modulation, pulse width 577 μs, mean power 0.25 W) on children (aged 10–14). Thirty-two subjects performed eight different tasks (simple reaction time, two-choice reaction time, ten-choice reaction time, vigilance task, and four levels of the n-back working memory, 0, 1, 2, 3). Subjects were exposed to both an active EMF (left hemisphere only) and a sham exposure separated by 24 h in a double-blind design. Duration of the EMF/sham was 50 min, occurring during the testing period. No significant effects were found on the children's cognitive functioning. A similar study was performed by Preece et al. [2005] to test the cognitive functioning of 18 children (age 10–12) during a left-hemisphere exposure to a mobile phone (GSM, 902 MHz, Nokia 3110). They used three different exposure conditions, power-off (true sham), 0.2 W power and at a 2 W peak to test the hypothesis that previous reported effects may be SAR dependent. During a 30 min EMF exposure, the children's performance was assessed by reaction time, accuracy and sensitivity to distraction (immediate word recognition, simple reaction time, digit vigilance, choice reaction time, spatial working memory, numeric working memory, delayed word recognition, picture recognition, dual attention task). No significant effects of the EMF exposure were found on performance.

In an attempt to mimic a ''real life'' exposure scenario, Besset et al. [2005] separated 55 subjects (27 male; 28 female) into two groups (EMF-on and EMF-off) matched for sex, age and IQ. For a 45-day testing period, subjects had a baseline period (3 days), exposure period (28 days) and a recovery period (14 days). During the exposure and recovery period, neuropsychological testing and rest periods were all interspersed and determined a priori. The cognitive tasks employed to assess EMF effects included screened information processing (simple and choice reaction time), attention capacity (digit span forward, spatial span forward, modified Stroop task, figure cancellation), memory function (auditory verbal learning, digit span backward, spatial span backward, number letter sequencing, Benton visual retention, perceptual priming), and motor function (Purdue pegboard). The actual EMF/sham exposures took place during the ''exposure'' and ''recovery'' periods using a mobile phone (900 MHz, 217 Hz modulation, pulse width 0.576 ms, SAR 0.54 W/kg). The exposure period attempted to mimic an actual phone call with subjects instructed to watch television with the phone in their preferred hand pressed to their ear (120 min exposure). Neuropsychological assessment was held 13 h after the EMF or sham exposure. No effects were found for the subjects exposed to the mobile phone. The authors of this study acknowledged that the longer time between exposure to the mobile phone and the subsequent testing (13 h) may have allowed for recovery of function and obscured any effects of the mobile phone upon subject performance. An overview of the results of these studies can be found in Table 5.

CONCLUDING REMARKS

Across the studies reviewed above, there are a number of points to consider regarding whether ELF MFs or ELF modulated RF fields affect the human brain and its subsequent output in the form of cognition and behavior. Certainly a number of varied EMF presentations are reviewed here that differ in intensity, duration of exposure and presentation format. Based on the reviewed publications investigating possible biological effects of ELF and RF exposure associated with mobile phones, the evidence suggests that brief exposures can induce measurable changes in human brain electrical activity, particularly in the alpha frequency band (8–13 Hz) over posterior regions of the scalp. This observation was also noted by Hamblin and Wood [2002] in their review on mobile phone effects on EEG and sleep variables. Interestingly, this

TABLE 5. Summary of ELF Modulated RF Field Effects Upon Performance Measures

Study	Parameters	Task	Effect on performance
Edelstyn and Oldershaw [2002]	900 MHz; 30 min LH exposure	Forward/backward digit span Forward/backward spatial span Serial subtraction Verbal fluency	↓ (increased processing speed) No effect ↓ (increased processing speed) No effect
Lass et al. [2002]	450 MHz (amplitude modulated 7 Hz); 10–20 min RH exposure	Trail making test Visual short-term memory Symbol digit modalities	↑ in error variance ↑ in error variance ↑ in error variance
Haarala et al. [2003a]	902 MHz (217 Hz); 30 min LH exposure.	Simple reaction time, choice reaction time, 10 choice reaction, subtraction task, verification and vigilance task	No effect
Haarala et al. [2003b]	902 MHz (217 Hz); 30 min LH exposure	n-Back task	No effect; ↓ in rCBF in left auditory cortex
Lee et al. [2003]	1900 MHz (217 Hz); <60 min RH exposure	Trails making test Sustained attention to response test	No effect ↓ (increased processing speed)
Smythe and Costall, [2003]	1800 MHz; 15 min LH exposure	Short-term recall Long-term recall	No effect ↓ in error rates in male subjects
Curcio et al. [2004]	902.4 MHz; 45 min LH exposure	Simple reaction time Arithmetic subtraction Visual search Acoustic choice reaction time	↓ (increased processing speed) No effect No effect ↓ (increased processing speed)
Haarala et al. [2004]	902 MHz (217 Hz); 65 min LH exposure	n-Back task	No effect
Maier et al. [2004]	902 MHz (217 Hz); 50 min LH exposure	Auditory discrimination task	↓ performance
Haarala et al. [2005]	902 MHz (217 Hz); 50 min LH exposure	Simple reaction time, two-choice reaction time, ten-choice reaction time, vigilance task, n-back working memory	No effect
Preece et al. [2005]	902 MHz; 30 min LH exposure	Immediate word recognition, simple reaction time, digit vigilance, choice reaction time, spatial working memory, numeric working memory, delayed word recognition, picture recognition, dual attention task	No effect
Besset et al. [2005]	900 MHz (217 Hz); 120 min LH and RH exposure	Simple reaction time, Choice reaction time, digit span forward, spatial span forward, modified Stroop task, figure cancellation, auditory verbal learning, digit span backward, spatial span backward, number letter sequencing, Benton visual retention, perceptual priming, Purdue pegboard	No effect

The ↑ and ↓ indicate whether performance on cognitive or perceptual tasks was affected due to magnetic field exposure. Exposure parameters are summarized and laterality of exposure described (right hemisphere, RH; left hemisphere, LH).

effect was also noted in several ELF studies as well [Cook et al., 2004, 2005; Ghione et al., 2005] suggesting that this observation may be a non-specific response to intermittent stimulation of pulsed fields, as continuously presented ELF fields [Lyskov et al., 1993; Crasson and Legros, 2005] do not tend to elicit the same effect. Alternatively, this also might be specific response to the ELF field exposure as the cw RF used in Huber et al. [2002] did not have a significant effect upon the EEG in contrast to the pulse-modulated RF field.

The effect of mobile phones upon various performance measures, mostly neuropsychological tasks of attention and working memory, are more equivocal. We are seeing more significant effects on physiological measures, but fewer effects upon performance. Why this might be the case is unclear. It is possible that the physiological effects are superfluous and result in no behavioral change. It is equally possible that the behavioral measures were not sensitive enough to detect changes in brain function. This is particularly relevant given the number of EMF-induced effects observed over the parietal/occipital regions. Many of the behavioral tests employed in the studies rely heavily on frontal or temporal lobe function. It must be considered that the variability in duration of field presentation combined with variability in post-presentation testing phase may also result in investigators missing key effects. This question remains to be determined.

One important point we focused on in this review is the timing of the EMF exposure, more specifically the observation of the ''delayed effect'' post-exposure. Eleven studies in this review observed significant field-related effects upon brain physiology and performance after the EMF was turned off. Other studies focused more upon the ''acute'' effects of EMF during the exposure period. While this is obviously a critical measure, particularly if one is interested in a detection mechanism, neglecting to continue measuring into the post-exposure period may have serious consequences for the interpretation of the data. As Huber et al. [2005] suggest, running an active and sham exposure in a crossover design may lead to field-induced contamination of the ''sham'' period. This ''delay'' or ''washout'' period must be considered further and rigorously tested. The metaphor of considering EMFs as similar to pharmaceutical agents has been previously considered, as evidenced by searches for dose dependence. However, unlike studies involving pharmaceutical agents (which have long post-administration follow-ups), the assessment of brain activity and performance is often measured during the EMF exposure period and not long afterwards. This allows for a very short measurement window for biological responses to EMF exposure. Brain and behavioral effects may continue to occur after the cessation of the field.

Current research on the effects of EMFs on human physiology and performance has demonstrated how careful one must be in designing a rigorous experiment. The choice of performance task will ultimately reflect the focus of the research, such as the investigation of whether mobile phones or power line frequencies will negatively affect human performance. If the EMF is found to have a non-significant effect upon the performance, the researcher may (reasonably) conclude that EMFs do not likely pose a serious effect upon this ability. However, based on the reviewed studies it seems that physiological measures are more likely to discover a significant biological effect compared to performance measures. One must also consider whether the lack of significant performance effects is also related to inadequate statistical power.

As discussed in Whittington and Podd [1996] and in Kazantzis et al. [1998], EMF effect sizes are generally small. Non-significant results may be due to the lack of power to detect them, rather than the absence of effect. Coupled with this statistical issue is the selection of performance tests that may be overly robust, that is, not adequate at discriminating subtle effects. Many of the performance tasks utilized in these studies are designed to discriminate between neurologically normal subjects and those suffering neurological impairment. If one considers a study with inadequate statistical power where the dependent variable is a very robust performance measure, the likelihood of a non-significant result may be quite high. If we also consider the ''timing'' variable that we have discussed in this review, that is, immediate versus delay assessment, the high number of studies reporting negative outcomes is not very surprising. It also makes the larger number of EMF studies finding significant physiological effects somewhat more understandable. It would seem that future research should be focused upon clarifying the existing physiological observations, which seem to be a relatively reliable and valid biological effect.

Of this current group of studies, the most promising technical development is the integration of bioelectromagnetics with functional imaging. Huber et al. [2002, 2005] and Haarala et al. [2004] have utilized PET to assess EMF effects upon rCBF. PET is a powerful technique that can assist in providing detailed information not only on changes in rCBF but also on metabolism and neuroreceptor occupancy levels in response to EMF exposure. With only three rCBF studies completed using PET, definitive answers are not yet available. However, based on the results of Huber et al. [2002, 2005] it would suggest that EMF can induce diffuse changes in rCBF significantly larger than the localized antennae region of the mobile phone. Furthermore, the Huber et al. [2005] study adds considerable support to the supposition that any biological effects of mobile phone exposure are likely non-thermal and are instead related to the low-frequency components of the modulation scheme of the mobile phone. This was also discussed in Hamblin and Wood's [2002] review paper on mobile phone effects upon EEG and sleep variables. ELF frequencies were found to be introduced via the time variation of power and the current from the battery as part of the modulation scheme in the GSM standard phones. For a 900 MHz phone, the fluctuating currents give rise to a constant pulsed magnetic field of 8 Hz which falls within the alpha frequency band (8–13 Hz).

A further consideration is the laterality of EMF exposure, particularly within studies of mobile phone effects. As evidenced in this review, 15 studies used a left hemisphere exposure, 5 used a right hemisphere exposure, 2 studies used a midline exposure, and 2 examined the effects on both hemispheres. It is clear that the choice of the hemisphere of exposure is somewhat arbitrary and not based on any a priori hypothesis with respect to the functional specialization of the hemisphere. Future studies should examine whether the choice of hemisphere of exposure will induce a specific functional change. This principle should also guide the choice of which performance measures might be most appropriate to assess possible EMF effects. This variable may also interact with the sex of the subject, as there are known differences in laterality between males and females. Two studies within this review [Smythe and Costall, 2003; Papageorgiou et al., 2004] found that sex interacted significantly with EMF exposure in both performance and EEG measures. Whether these observations are related to true sex differences remains to be verified. While these effects may be subtle, they are known neurological observations.

A suggestion discussed in our previous review [Cook et al., 2002] is further consideration of personality and individual differences in response to EMF exposure. To the best of our knowledge, only Stevens [2001] has addressed how individual differences in responsivity to a MF may exist. He noted that subjects could be grouped based on their skin conductance responses (a measure of arousal) to a 50 Hz ELF MF, finding ‘‘high,’’ ‘‘low,’’ and ‘‘no’’ responders to the field. Is there a physiological factor(s) that might determine the response characteristics of the subject? Can the direction of a subject’s physiological response be predicted a priori by knowing this factor? These are important questions that must be answered. A recent study suggests that a subject’s task-related BOLD (blood oxygenation level dependent) response in an fMRI experiment can be predicted by something as simple as a personality inventory [Kumari et al., 2004]. Similarly, Gianaros et al. [2005] examined the role of individual differences in cardiovascular reactivity using fMRI. Subjects who displayed different stress reactions (strong increases and strong decreases) in blood pressure were selected. It was determined that ‘‘high reactors’’ (those displaying exaggerated blood pressure responses) showed an increase in posterior cingulate activity, while ‘‘low reactors’’ (those displaying attenuated blood pressure responses) displayed a decrease in rCBF over the posterior cingulate region. The authors have speculated that the differential activity in this brain region may be a neural correlate of individual differences in cardiovascular reactivity. Observations such as these lead one to speculate whether there are such variables to help explain some of the discrepancies seen in human EMF experiments. One concluding thought was stated by Fuller et al. [2003]: ‘‘The interaction of magnetic fields with the nervous system clearly has complicated manifestations.’’

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