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Article *in* Bioelectromagnetics · March 2002

DOI: 10.1002/bem.107 · Source: PubMed

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Bioelectromagnetics 23:144–157 (2002)
DOI 10.1002/bem.107

Human Electrophysiological and Cognitive Effects of Exposure to ELF Magnetic and ELF Modulated RF and Microwave Fields: A Review of Recent Studies

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The investigation of weak (< 500 μT), extremely low frequency (ELF, 0–300 Hz) magnetic field (MF) exposure upon human cognition and electrophysiology has yielded incomplete and contradictory evidence that MFs interact with human biology. This may be due to the small number of studies undertaken examining ELF MF effects upon the human electroencephalogram (EEG), and the associated analysis of evoked related potentials (ERPs). Relatively few studies have examined how MF exposure may affect cognitive and perceptual processing in human subjects. The introduction of this review considers some of the recent studies of ELF MF exposure upon the EEG, ERPs and cognitive and perceptual tasks. We also consider some of the confounding factors within current human MF studies and suggest some new strategies for further experimentation. Bioelectromagnetics 23:144–157, 2002. © 2002 Wiley-Liss, Inc.

Key words: electroencephalography (EEG); evoked related potential (ERP); event related potential; cognitive processing

INTRODUCTION

Experimental investigations of weak (< 500 μT), extremely low frequency magnetic field (ELF MF, 0–300 Hz [Tenforde, 1996]) effects on human physiology have yielded some evidence of effect in a number of different areas, such as heart rate variability, sleep disturbance and melatonin suppression [NIEHS Working Group Report, 1998; Graham et al., 2000; Sastre et al., 2000]. Few studies have examined the effects of MFs (Magnetic fields) upon the brain's electrical activity and fewer still address perceptual and cognitive effects of MF exposure. As in most bioelectromagnetics studies, there have been inconsistencies in results between experiments. There are several possible reasons for this, such as differences in experimental protocol and MF characteristics (intensity, frequency, waveform, exposure duration), which may increase the variance within and across studies. However, in studies involving humans, particularly in electrophysiology, there are a number of extraneous factors that are not always explicitly addressed. For example, the resting EEG can be affected by both smoking and arousal state, as addressed by Cook et al. [1995], leading to significantly different frequency band dominance. Controlling for such factors can decrease the variance and hence increase the power to detect a small effect within a given study.

The reviewed experiments focus mainly upon the effects of ELF MFs upon human neurophysiology and psychophysiology. Although the use of transcranial magnetic stimulation in studies of human cognition is becoming more prevalent [Jahanshahi and Rothwell, 2000; Pascual-Leone et al., 2000], such experiments are outside the range of 'weak' magnetic fields and hence are not considered in this review. Rather, the focus of this paper will be to review some of the recent work on human electroencephalography (EEG) and cognitive studies of weak, extremely low frequency magnetic field effects (ELF MF). We have decided to include work on ELF modulated radiofrequency (RF) and microwave exposure associated with cellular phones. It

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Received 20 November 2001; Final revision received 4 May 2001

has been suggested that biological effects of such exposure are related to the ELF modulation and the demodulation which could occur in exposed biological systems [Barnes, 1996; Postow and Swicord, 1996]. Therefore the focus of the review is an assessment of current ELF MF research upon awake human cognitive processing assessed by EEG and ERP.

Magnetic Field Effects Upon Human Electrophysiology

In human studies, assessing the effects of static magnetic fields, Bell et al. [1991] found that 35% of subjects ($n = 20$) exposed to a 93 μT static magnetic field (78 μT applied static field, vector summed with the Earth's geomagnetic field) displayed increased spectral power in the EEG recorded from occipital, central and parietal regions. Fuller et al. [1995] found an increase in epileptiform activity in six epileptic patients undergoing presurgical evaluation after an exposure (10 s on followed by 40 s off) to a weak (1–2 mT) DC MF. Using a similar procedure, Dobson et al. [2000a] also found increased epileptiform activity after exposing three epileptic subjects to a 0.9–1.8 mT DC MF using two different protocols (maximal dB/dt vs. minimal dB/dt). In a subsequent study using a larger subject size, Dobson et al. [2000b] offered further support for the previous work, finding that a weak DC MF (1–4 mT) elicited changes in EEG activity in 50% ($n = 10$) of the epileptic patients tested.

In studies examining the effects of alternating ELF MF upon the resting EEG, Bell et al. [1991] found that 80% of subjects ($n = 20$) responded to a 60 Hz MF (25–50 μT_{rms}) displaying an increase in EEG spectral power (Fourier transformed) recorded from central and parietal regions. In contrast, Bell et al. [1994a] found decreased EEG activity in the occipital region but not the central or parietal areas after exposure to a 10 Hz, 100 μT_{rms} MF. Bell et al. [1994b] found that a 10 Hz, 40 μT_{rms} MF was more effective than a 1.5 Hz, 20 μT_{rms} MF in eliciting increases in EEG activity at the frequency of stimulation (10 Hz MF preferentially affecting 10 Hz EEG, 1.5 Hz MF affecting 1.5 Hz EEG, most effective during the 40 μT exposure). Schienle et al. [1996] found that a 10 kHz MF (approximately 5 μT_{pk}), pulsed between 6.6 and 20 Hz significantly reduced EEG spectral power within a narrow frequency band of 10.0–10.75 Hz (alpha range), most pronounced within the parietal region. Marino et al. [1996] found increases in spectral power mainly at higher EEG frequencies (>10 Hz) in the central, parietal and occipital regions at two different field conditions (10 and 1.5 Hz both at 80 μT_{rms}). Heusser et al. [1997] also found increases in occipital EEG spectral power in the beta (12.5–25.0 Hz) and theta band (3.5–7.5 Hz) after exposure to a 3 Hz (0.1 mT_{pk}) MF.

The studies examined in this section provide a brief overview of some recent ELF MF exposure upon the resting, awake human EEG. It is difficult to conclude any specific effects in terms of EEG frequency or brain region, due in part to the variations in EEG analysis techniques, including the number and placement of electrodes and the analysis of the data (time vs. frequency analysis). In addition, due to the paucity of data in this particular subject area, any conclusions that could be drawn should only be considered tentative. An overview of the results of these studies can be found in Table 1.

Magnetic Field Effects Upon Human Sensory Perception and Cognition

In combined experiments of cognition and electrophysiology, probably the most common method used is the evoked related potential (ERP) [for an in depth review, see Başar, 2000]. The presentation of a stimulus typically results in a transient electrophysiological signal, which is termed the evoked or event related potential. The evoked signal is averaged across repeated trials and labeled according to component as N or P, signifying negative or positive peaks appearing in the waveform at designated intervals. For example, the P300 is a midlatency positive peak that appears approximately 300 ms after stimulus onset and is associated with information processing. The ERP is a relatively objective quantification of cognitive and sensory processing within the brain, but it is not without problems regarding inter and intra subject variation [Doppelmayr et al. 1998]. In experiments, investigating ELF MF effects upon cognitive or sensory processing in humans, tasks typically involve reaction time, sensory discrimination, and working memory. These tests can be utilized to investigate performance itself or be used in conjunction with ERPs. It is our intention to discuss these two approaches separately.

Evoked related potentials. Cook et al. [1992] found that the magnitude of the P300 component of the auditory ERP increased after a 6 h whole body electric and MF exposure (60 Hz, 9 kV/m electric field; 60 Hz, 20 μT magnetic field) compared to sham exposure. The visual ERP component amplitudes were not affected by ELF MF exposure. This experiment also noted a slight increase in reaction time in field exposed subjects compared with sham exposed subjects. Lyskov et al. [1993a] found significant increases in alpha (7–13 Hz) and beta (14–25 Hz) activity after a 15 min exposure to an intermittent magnetic field

TABLE 1. Summary of ELF Magnetic Field Effects Upon the Electroencephalogram (EEG)*

		Frontal				Central parietal				Occipital			
Study	Parameters	Delta 0–3 Hz	Theta 4–7 Hz	Alpha 8–13 Hz	Beta 14–20 Hz	Delta 0–3 Hz	Theta 4–7 Hz	Alpha 8–13 Hz	Beta 14–20 Hz	Delta 0–3 Hz	Theta 4–7 Hz	Alpha 8–13 Hz	Beta 14–20 Hz
Bell et al. [1991]	60 Hz 25–50 μT; < 10 min exposure					↑	↑	↑	↑	↑	↑	↑	↑
Lyskov et al. [1993b]	45 Hz 1.26 mT; 60 min exposure	↓	↓		↑	↓	↓					↑	
Bell et al. [1994a]	10 Hz 100 μT; 2 s exposure											↓	
Bell et al. [1994b]	10 Hz, 1.5 Hz 40 μT, 20 μT; 10 min exposure							↑					
Schienle et al. [1996]	10 kHz ∼5 μT; 10 min exposure							↓					
Marino et al. [1996]	10 Hz, 1.5 Hz 80 μT; 2 s exposure							↑	↑			↑	↑
Heusser et al. [1997]	3 Hz 0.1 mT 20 min exposure										↑		↑
Bell et al. [1991]	DC 93 μT < 10 min exposure					↑							
Fuller et al. [1995]	DC 1–2 mT < 5 min.				↑ epileptiform activity (medial temporal lobe)								
Dobson et al. [2000a]	0.9–1.8 mT < 10 min.				↑ epileptiform activity (medial temporal lobe)								
Dobson et al. [2000b]	1–4 mT < 60 min.				↑ epileptiform activity (medial temporal lobe)								

*Exposure increases (↑) or decreases (↓) activity.

($1.26\ mT_{rms}$; frequency 45 Hz; 1 s on-off). This study also noted significant MF related effects upon auditory ERP waveforms (decreased N100 latency and amplitude), but the effect upon reaction time was not significant. A subsequent study by Lyskov et al. [1993b] using the same experimental procedure, but with a longer exposure period (60 min), found decreased delta (1–3 Hz) and theta (4–7 Hz) spectral power at frontal, central, and parietal regions. They also found increased alpha (7–13 Hz) power at the occipital region and beta (14–25 Hz) in the frontal region.

Sartucci et al. [1997] found that a MF exposure (+70 to −20 μT; 0.026, 0.043, and 0.067 Hz presented simultaneously on three nested orthogonal coil pairs) reduced the amplitude of pain related somatosensory evoked potentials (N150 and P250 waves) compared to sham exposure. The exposure duration was 2 h and the complicated nature of these fields was chosen because they had previously been shown to produce orientation disturbances in pigeons [Ioale and Guidarini, 1985], affect the activity of the endogenous opioids [Papi et al., 1992] and induce hyperalgesia in humans [Papi et al., 1995]. The DC offset was the result of the ambient geomagnetic field.

Across two different experiments, Crasson et al. [1999] examined the effects of 50 Hz, $100\ \mu T_{rms}$ MF exposure. In one experiment, significant effects were found for the dichotic listening task (a test of selective attention to auditory stimuli), with decreased N100 (negative peak, 100 ms poststimulus onset) amplitude in the frontal and parietal regions after intermittent (15 s on-off) MF exposure, but not during continuous MF or sham exposure. There was also a significant difference between the testing times (1330 and 1630 h), with the earlier group displaying differential reactivity (higher amplitude waveforms in the 1330 h group) in a number of ERP waveforms, such as the P300. In a second experiment, significant differences were again found for dichotic listening, but with higher N100 amplitude in the attend-right condition at the central and parietal regions after continuous magnetic field exposure. Reaction time was found to be significantly slower after continuous MF exposure, compared to sham. In a study to assess the effects of ELF MF on the early sensory components of the ERP, Graham et al. [1999] exposed subjects to an intermittent (15 s on-off) 60 Hz MF (14.1 or 28.3 μT) for 45 min and found no effect upon auditory brainstem (BAEP), visual (VEP) or somatosensory evoked potential (SEP) waveforms.

Much like the studies of MF effects upon the resting EEG reviewed earlier, the results of the evoked potential studies of MF effects are similarly difficult to interpret, due in part to the small number of ERP studies of MF effects. Certainly, the studies suggest that MF exposure may affect the evoked waveform in different modalities. However, due to the variability of results, conclusions regarding the specificity of effect upon evoked waveforms and hence, cognitive processing, should be made cautiously. But in these cited studies, one could argue that there seems to be an effect on the mid to late latency evoked related potentials, such as the P300. This waveform is typically elicited in an 'oddball' paradigm, where a subject is asked to attend to an infrequently presented sensory stimulus.

The P300 is generally associated with cognitive or information processing, as opposed to early ERP components thought to reflect sensory transduction of stimuli. Recent neuroimaging studies combining EEG and functional MRI (fMRI), correlating electrophysiological signals with blood oxygenation level dependent (BOLD) activation, have localized a number of key brain areas involved in the generation of the P300 response, indicating a distributed network of brain areas associated with infrequent target detection, including the inferior parietal cortex, lateral and midline frontal cortex and the insular cortex [Linden et al., 1999].

If there is an effect of weak ELF MF upon the P300, it would be affecting an individual's capacity to respond rapidly to novel or unpredictable stimuli in the immediate environment. Depending upon the direction of the effect upon the P300, MFs could exert a facilitating or debilitating effect. However, further experiments are needed to confirm these initial studies. An overview of the results of these studies can be found in Table 2.

Sensory, perceptual and cognitive performance. An investigation of MF effects on reaction time by Podd et al. [1995] revealed no significant effects on performance after exposure to a 0.1 and 0.2 Hz, $1.1\ mT_{pk}$ MF. A second experiment in this study by Podd et al. examined reaction time under 3 different conditions (no field, 0.2 Hz and 43 Hz, $0.100\ mT_{rms}$) to assess predicted AC/DC field interactions by parametric resonance mechanisms. No significant effects on reaction time were reported for any conditions. Papi et al. [1995] investigated pain perception, as defined by sensory thresholds, during MF exposure and found that the dental sensory threshold was significantly reduced during exposure to the same ELF MF used by Sartucci et al. [1997] (+70 and −20 μT). Whittington et al. [1996] found that subjects' exposure to a 50 Hz, $100\ \mu T_{rms}$ intermittent (1 s on-off) MF affected reaction time in a visual duration discrimination task with three levels of difficulty. This MF effect interacted with the task difficulty; subjects showed decreased reaction

TABLE 2. Summary of ELF Magnetic Field Effects Upon Evoked Related Potentials and Task Related EEG*

Study	Parameters	Frontal	Central parietal	Temporal
Cook et al. [1992]	60 Hz, 20 μT; 6 h exposure		↑ P300 (auditory)	
Lyskov et al. [1993a]	45 Hz, 1.26 mT; 15 min. exposure			↓ N100 (auditory)
Sartucci et al. [1997]	<1 Hz, 20–70 μT 2 h exposure		↓ N150, P250 (somatosensory)	
Crasson et al. [1999] exp1	50 Hz, 100 μT 30 min. exposure	↓ N100 (auditory)	↓ N100 (auditory)	
Crasson et al. [1999] exp2	50 Hz, 100 μT 30 min. exposure		↑ N100 (auditory)	
Graham et al. [1999]	60 Hz, 14.1 μT, 28.3 μT 45 min. exposure		Not significant	

*Exposure increases (↑) or decreases (↓) activity.

time when exposed to the 100 μT MF relative to sham exposure, with no evidence that accuracy on the task was affected by MF exposure. A study by Kazantzis et al. [1998] using a 50 Hz, 100 μT_{rms} intermittent (1 s on-off) MF examined accuracy (percentage correct) in a visual duration discrimination task. It was found that acute MF exposure produced a small increase in accuracy, but only at the most difficult level of the visual task, a result consistent with Whittington et al. [1996].

In an experiment assessing MF effects upon a variety of neuropsychological tasks of executive function, Preece et al. [1998] exposed subjects to a 50 Hz, 0.6 mT oscillating MF and a 0.6 mT DC MF. It was found that 50 Hz MF, but not the DC field, decreased accuracy in a numerical working memory (the ability to transiently hold digits in ‘in mind’), decreased word recognition sensitivity (discriminating words shown originally from novel or ‘distracter’ words) and decreased accuracy on a ‘choice reaction time’ task (accuracy of pressing ‘Yes’ or ‘No’ buttons correctly as they appear on computer screen). Cook et al. [1999] found that subjects exposed to a specific, frequency modulated MF (10 μT) displayed significant increases in subjective time estimations, relative to baseline estimations.

A recent study by Keetley et al. [2001] on 50 Hz, 28 μT MF exposure and performance on a battery of neuropsychological tests further suggests that MF do elicit effects upon executive function. Performance on the Trails Making B task, an assessment of prefrontal and parietal cortical activity, was significantly worsened (processing speed decreased) after MF exposure. In order to assess MF effects upon human arousal and affective (emotional) responsiveness, Stevens [2001] exposed subjects to a sinusoidally modulated 20 Hz, 50 μT MF. It was found that subjects tended to display higher, more positive affective responses to visual stimuli during field exposure compared to the sham condition. Subjects’ arousal, as measured by skin conductance, differed categorically in the presence of the MF, with 48% of subjects displaying a lowered skin conductance (lower arousal), 34% no reaction and 17% displaying a higher skin conductance (higher arousal). Interestingly, those subjects displaying a lowered skin conductance or having no reaction gave higher affective ratings, while the higher skin conductance group gave lower affective ratings.

The studies examining cognitive, behavioral or perceptual effects of MF exposure are also quite variable in terms of methodology and results. However, despite the variations, there are some intriguing results that suggest a specificity of effect, with task dependent MF effects emerging. Several studies suggest that MFs significantly affect a subject’s cognitive or perceptual activity when the task difficulty increases. An examination of the functional neuroimaging literature suggests that the estimation of duration by discrimination between visual stimuli or prospective estimation of a fixed time duration, involves predominantly frontal and parietal cortical activation [Maquet et al., 1996]. A more recent study combining ERP and PET data of visual duration discrimination found that the actual decision making portion of the task, choosing the stimulus with the longer duration, activated the right frontal cortex [Pouthas et al., 2000]. In light of the experimental results of ELF MF exposure upon duration estimation by Whittington et al. [1996], as well as the neuropsychological tests used by Preece et al. [1998], and Shardey et al. [2001], evidence suggests that weak field exposure can affect frontal and parietal cortex activity, particularly during tasks of executive function. The results of these studies can be found in Table 3.

TABLE 3. Summary of ELF Magnetic Field Effects Upon Cognitive and Perceptual Tasks*

Study	Parameters	Task	Effect of performance
Podd et al. [1995]	0.1, 0.2 Hz, 1.1 mT 300 s exposure	Reaction time	No effect
Papi et al. [1995]	<1 Hz, 20–70 μT 2 h exposure	Pain perception	↓ threshold
Whittington et al. [1996]	50 Hz, 100 μT 9 min. exposure	Reaction time	↓ (increased processing speed)
		Accuracy (discrimation task)	no effect
Kazantzis et al. [1996]	50 Hz, 100 μT 7.9 min. exposure	Accuracy (discrimation task)	↑
Preece et al. [1998]	50 Hz, 0.6 mT; n/g	Immediate word recall	No effect
		Picture presentation	No effect
		Simple reaction time	No effect
		Digit vigilance	No effect
		Choice reaction time	↓ accuracy
		Spatial working memory	No effect
		Numerical working memory	↓ accuracy
		Delay word recall	No effect
		Delay word recognition	↓ sensitivity
		Delay picture recognition	No effect
Cook et al. [1999]	Pulsed 0–1 kHz, 5 μT; 30 min. exposure	Time estimation	↑
Stevens [2001]	20 Hz; 50 μT <5 min. (estimated)	Affective picture rating	↑ positive affective responses
Shardey et al. [in press]	50 Hz, 28 μT 50 min. exposure	Rey auditory verbal learning	No effect
		Digit span	No effect
		Digit symbol	No effect
		Symbol digit modalities	No effect
		Speed of comprehension	No effect
		Trails making test	↑ speed (decreased performance)

*Exposure increases (↑) or decreases (↓) activity.
n/g, not given.

ELF-modulated radiofrequency and microwave exposure. The large increase in cellular phone use over the last several years has made the investigation into possible health effects of electromagnetic field exposure of the brain and hence cognitive and behavioural performance, a critical experimental area. One investigative factor in assessing the risk of cellular phone use is the modulation or variation of the radiofrequency (RF) signal. The carrier signal for the Global System for Mobile Communications (GSM) is pulsed in the extremely low frequency (ELF) range at 217 Hz, with a pulse width of 577 μs. It has been suggested that biological systems may demodulate this RF signal and be responsive only if RF is ELF modulated [Barnes, 1996; Postow and Swicord, 1996]. For example, processes which respond to the square of the RF field, such as energy deposition, intrinsically result in demodulation.

To assess whether a very brief EMF exposure (<5 min) could affect the awake, resting EEG, Röschke and Mann [1997] found that a 916.2 MHz EMF pulsed at 217 Hz did not cause any significant alteration in normal background EEG. Eulitz et al. [1998] found that a 916.2 MHz EMF pulsed at 217 Hz significantly modulated the beta frequency band (18.75–31.25 Hz) in the P300 time window over the central region of the brain. This effect was dependent upon the activity of the exposed hemisphere during an auditory discrimination task, a result that only occurred in conjunction with task related processing and was somewhat more pronounced over the right hemisphere. Freude et al. [1998] found that a 916.2 MHz EMF pulsed at 217 Hz resulted in significant decreases in brain slow potentials, most pronounced in the right hemisphere central and temporal-parietal-occipital areas, but not frontal regions. A further study by Freude et al. [2000] using the same exposure conditions confirmed results of their previous experiment, finding decreased event related slow potentials at central and parieto-temporo-occipital regions, but not at the frontal regions and without decrement in performance task measures.

Krause et al. [2000a] found that a 902 MHz EMF pulsed at 217 Hz increased the relative EEG power in the 8–10 Hz (alpha) range, a task specific field effect on the retrieval portion of a working memory task. However, in this study EMF altered evoked related synchronizations and desynchronizations in different

EEG frequency bands diversely as a function of time and memory task. Krause et al. [2000b] assessed EEG effects and visual working memory performance during exposure to a 902 MHz EMF pulsed at 217 Hz. No effect of EMF was found on reaction time or performance of the visual working memory (memory for visually presented digits 1, 2 or 3 trials earlier, the 'n-back') task. However, EMF did affect specific EEG frequency bands in a task dependent manner, specifically around the 8 Hz (alpha) range, a finding in line with their previous study [Krause et al., 2000a].

In order to investigate the effects on cognitive function, Preece et al. [1999] exposed subjects to a 915 MHz MF modulated at 217 Hz and continuous wave (CW) 915 MHz MF while performing a variety of different tasks (memory recall, recognition and reaction time). The CW 915 MHz signal caused a decrease in choice reaction time i.e., processing time increased (time taken to respond to a 'yes' or 'no' appearing on a computer screen), but found little effect upon several working memory and attentional tasks. The 915 MHz ELF modulated signal produced no effect in this study.

Koivisto et al. [2000a] examined how a 902 MHz EMF pulsed at 217 Hz affected cognitive processing as assessed by reaction time (RT) tasks. It was found that simple reaction time as well as tasks involving vigilance (requiring attention to infrequent target) and mental arithmetic (subtracting the target number from nine and pressing the button for the remainder) was affected by MF exposure. Accuracy was improved during the vigilance task with subjects reacting to fewer 'false alarms' during field on than in field off exposure. In a further study, Koivisto et al. [2000b] examined working memory and reaction times during exposure to a 902 MHz EMF pulsed at 217 Hz. The most significant finding in this study was that the effect of EMF exposure was dependent on the level of cognitive load with a significant decrease in reaction time in the highest difficulty condition (memory for digits three trials back). EMF exposure in this study had no effect on accuracy in the working memory task.

In one of the first studies to assess how frequent exposure to cellular phone EMFs may affect regular users, Lee et al. [2001] compared regular cellular phone users (usage, in minutes, ranging from 175 to 27, 240) to matched nonusing controls. On several tests of attention, the regular users of cellular phones were found to perform significantly better than controls on two parts of the Trails Making Test (a task of executive functioning, based on visuomotor speed and cognitive set shifting). The authors rightfully interpret that this result may be speculative, since regular cell phone users may simply be better at multitasking than nonusers. Most recently, Koivisto et al. [2001] assessed whether the awareness of subjective sensations, such as headache, dizziness, fatigue, and skin irritation (redness, warmth, itchiness, tingling), were influenced by exposure to a 902 MHz RF pulsed at 217 Hz. Results indicated that there were no significant differences in subjective sensations between the exposure and control conditions.

Some studies lead one to conclude that brief exposure to fields of this frequency and intensity may actually have a facilitative effect on some performance measures with increased processing speeds and increased reaction times to some cognitive tasks. At present, evidence suggests that brief exposures to ELF modulated RF do have an effect upon cognition and electrophysiology. In a new area such as this, further experimentation with a more rigorous and standardized methodology for EEG analysis is needed. Additionally, test phones have been used in many studies; and variations exist in the energy distribution between different models, positioning, and thermal effects from the phone battery, all of which will have an influence upon the recording variables in studies of EEG effects. It would be interesting to evaluate the effects of an ELF MF having the same ELF components as a demodulated ELF modulated RF. Of course, spectral content of the ELF MF would be dependent on the mechanism of demodulation of the RF, still a very poorly understood mechanism. Perhaps, this factor explains why no literature exists. An overview of the results of these studies can be found in Tables 4 and 5.

A Consideration of Future Experiments

Although by no means a complete overview of human studies of MF effects, the group of experiments cited in the present review are a representative sample of recent studies of possible electrophysiological and cognition effects. As one of the most common problems in bioelectromagnetics is a lack of reproducibility of results, a concerted effort should be undertaken to reduce the variance within human studies of cognition and EEG. This has been emphasized in recent studies by Whittington et al. [1996] and Kazantzis et al. [1998] who have suggested a number of methods of increasing statistical power in human experiments assessing MF effects such as increasing the number of subjects in a study and relaxing the conventional 0.05 significance level. To further complement such suggestions, the following section is designed to elucidate some further ideas that may improve or encourage new studies.

Resting or baseline state. In electrophysiological and neuroimaging studies of cognition, the resting or

TABLE 4. Summary of ELF Modulated RF and MW Field Effects Upon Evoked Related Potentials and Task Related EEG*

Study	Parameters	Central parietal	Temporal	Occipital
Röschke et al. [1997]	900 MHz (217 Hz), 8.0 W_{pk}; 3.5 min. exposure	No significance		
Eulitz et al. [1998]	917.2 MHz (217 Hz), 2.8 W_{pk}; n/g	↓ P300		
Freude et al. [1998]	916.2 MHz (217 Hz) 2.8 W_{pk}; 3–5 min. exposure	↓ slow potential (SP)	↓ (SP)	↓ (SP)
Freude et al. [2000]	916.2 MHz (217 Hz) 2.8 W_{pk}; 3–5 min. exposure	↓ slow potential (SP)	↓ (SP)	↓ (SP)
Krause et al. [2000a]	902 MHz (217 Hz), 2.0 W_{pk}; 30 min. exposure	↑ in averaged relative alpha power		
Krause et al. [2000b]	902 MHz (217 Hz) 2.0 W_{pk}; 30 min. exposure	Modulation of event related alpha activity		

*Exposure increases (↑) or decreases (↓) activity.
n/g, not given.

baseline state in the human subject forms a reference from which comparisons to experimental tasks can be made. Raichle et al. [2001] suggests that the baseline state is fundamental to the proper understanding of results in complex systems such as the human brain. Defining the baseline state is a particular challenge; left unconstrained, its activity will vary unpredictably. Binder et al. [1999] also addressed this issue with respect to functional imaging studies, but the principle and results of the study are very applicable to experiments assessing human brain responses to MF exposure. It was found that the 'resting state' was

TABLE 5. Summary of ELF Modulated RF and MW Field Effects Upon Cognitive and Perceptual Tasks*

Study	Parameters	Task	Effect on performance
Preece et al. [1999]	915 MHz CW, ~1 W; 915 MHz (217 Hz), 0.125 W; n/g	Immediate word recall	No effect
		Picture presentation	No effect
		Simple reaction time	No effect
		Digit vigilance	No effect
		Choice reaction time	↓ (increased processing speed)
		Spatial working memory	No effect
		Numeric working memory	No effect
		Delayed word recall	No effect
		Delayed word recognition	No effect
		Delayed picture recognition	No effect
Koivisto et al. [2000a]	902 MHz (217 Hz), 2.0 W_{pk}; 60 min. exposure	Simple reaction time	↓ (increased processing speed)
		Vigilance task	↓ false alarms (increased attentiveness)
Koivisto et al. [2000b]	902 MHz (217 Hz), 2.0 W_{pk}; 30 min. exposure	Reaction time	↓ (increased processing speed)
Lee et al. [2001]	n/a	Symbol digit	No effect
		Stroop colour word	No effect
		Trails making test	↓ time (increased processing speed)
Koivisto et al. [2001]	902 MHz (217 Hz), 2.0 W_{pk}; 30–60 min. exposure	Questionnaire (subjective symptoms)	No effect

*Exposure decreases (↓) activity.
n/a, not applicable; n/g, not given.

not a state of neural inactivity, but was characterized by activity within the medial occipital, parietal and dorsal prefrontal regions. A ^{15}O-H_2O positron emission tomography (PET) study examining the 'resting state of consciousness' also noted activity within the dorsal-lateral and orbital-frontal cortex region, anterior cingulate, left parietal and occipital cortices, striatal, thalamic and cerebellar regions [Lou et al., 1999]. Most recently, Mazoyer et al. [2001] confirmed that the 'resting state' does seem to be dominated by episodic autobiographical memory, part of a large scale frontal-parietal network that operates when a subject is engaged in REST (random episodic silent thinking). A recent study using nonlinear EEG analysis (correlation dimension, an indice of EEG signal complexity) across control and clinical groups during a resting, eyes closed condition found that the central region (C3, C4) and electrodes closer to the mid-line possessed high dimensional values, whereas the occipital region (O1, O2) possessed low dimensional values, irrespective of the subjects' clinical status [Bhattacharya, 2000].

As noted earlier in this review, the central-parietal region seems to be somewhat more affected during different magnetic field exposure paradigms. This, however, may simply be a resultant interaction with a region-specific resting state. Mulholland [1995] also emphasized that a cautious interpretation of the resting state should be made with respect to EEG studies, since measurements are typically taken during a state of 'behavioral stillness' and are therefore somewhat artificial. Extrapolations of results to a 'real world' setting may therefore not be completely applicable.

Given these results, future studies might consider a more uniform 'baseline' state when measuring the EEG with minimal variance in sensory stimulation. This may include characterizing a single baseline state, such as 'eyes closed, sitting quietly,' and supplementing that with 'eyes open, minimal activity' with both a sham and a MF exposure for both states. Furthermore, closer attention should be paid to the ambient light levels during EEG recording, since recent studies examining the effects of ELF MF upon standing balance noted a differential effect between low light and high light conditions in baseline and exposure conditions [Prato et al., 2001]. More recently, in his study of arousal and affective responses to MF exposure, Stevens [2001] has suggested that future MF studies might benefit from dividing subjects into groups based on the degree of resting physiological activity to predict possible differences in their task responses during MF exposure. To fully appreciate the effects found in MF experiments on EEG and cognition, attention to such issues as resting or baseline state are critical in the design and interpretation of future MF effects studies.

Personality and individual differences. One variable that is peripherally related to a foreknowledge of the resting state is the 'personality' of the human subject. Although it is a difficult concept to quantify, personality is often defined as a characteristic or baseline cognitive or behavioral state of a human [Sugiura et al., 2000]. In fact, personality may be one of the largest contributions to extraneous variance in human studies which makes controlling its effect in bioelectromagnetics experiments all the more important. The control of personality effects in trials for medical and pharmacological research is considered a necessary covariate to allow experimenters to investigate 'true' drug side effects from those that may arise due to personality factors, such as negative affectivity. The control of personality factors within a study is therefore necessary to increase the power to detect a treatment effect [Swartzman and Burkell, 1998].

Studies of ERP and cognitive neurophysiology have noted that different personality types display quantitatively different ERPs in response to sensory and cognitive manipulation [Hegerl et al. 1995]. Two recent neuroimaging studies using PET and single photon emission computed tomography [SPECT], respectively, found that different personality types could be differentiated on the basis of their resting state. Extraverts and introverts display significantly different baseline activity [Johnson et al., 1999], while 'novelty-seekers' and 'harm avoiders' have also been shown to differ according to their baseline state [Sugiura et al., 2000]. Pizzagalli et al. [2000] found that subjects who professed a high degree of belief in the 'paranormal' (belief in extrasensory perception, magical ideation) displayed significantly different active neural populations during resting conditions compared to skeptical subjects (nonbelievers). Believers in paranormal phenomenon displayed greater baseline EEG beta activity (~18.5–21 Hz) that was strongly lateralized to the right hemisphere, whereas the more skeptical subjects were more left hemisphere lateralized in this frequency band. Persinger [1993] has consistently emphasized the significant effects of personality factors in human MF experiments and has suggested that a person's stable behavioral and physiological reactivity predisposes one towards MF reactivity [Ruttan et al., 1990; Persinger and Makarec, 1992]. Crasson et al. [1999] noted in their study, that hedonic persons tend to be more responsive to MF exposure. This topic has not been pursued to a large degree and may explain some of the so called electro sensitive persons, who consistently report effects due to weak field exposure [NIEHS Working Group Report, 1998].

Care should especially be made in reducing or controlling for other forms of inter subject and intra subject variance in human studies of cognitive and behavioral effects, something previously suggested by both Podd et al. [1995] and Crasson et al. [1999]. This includes noting the state of the subject entering the study, such as mood and arousal level. Recent studies suggest that there are small, but significant time of day effects upon the EEG, owing to ultradian and circadian rhythmicity [Chapotot et al., 2000; Lafrance and Dumont, 2000; Maquet, 2000]. If female subjects are participating in the experiment, a consideration of menstrual phase should be noted, since some studies have indicated the existence of menstrual phase related EEG and performance effects [Creutzfeldt, et al., 1976; Solis-Ortiz et al., 1994]. Another variable to be considered would be recent pharmacological intake, including alcohol or prescription medication. The ingestion of a recent meal is also known to affect EEG and ERP components [Hoffman and Polich, 1998].

Analysis of the electroencephalogram (EEG). Studies of weak MF effects upon the EEG lack a general theoretical underpinning. Marino [1995] and Marino et al. [2000] have hypothesized that deterministic chaos could be a possible explanation of the inconsistent effects found in bioelectromagnetics. Nonlinear dynamics may be a framework from which to consider some of the variable results of prior studies in this review. Future studies might consider augmenting traditional linear analysis with nonlinear dynamical methods, since there are indications that the electrical activity of the brain may be governed by chaotic dynamics [Pradhan and Dutt, 1993; Röschke et al., 1997; Freeman, 2000]. If linear analysis is utilized to describe a nonlinear system, significant results could be masked. Röschke and Aldenhoff [1992] examined slow wave sleep in the cat and found similar spectral power estimates in the auditory cortex and hippocampus, but that these regions possessed different dimensionality estimates, an index of signal complexity. This result suggests that information may be gained from using nonlinear analyses that may not be acquired from traditional linear techniques, such as frequency analysis obtained by Fourier transformations. If there is an element of deterministic chaos within the EEG signal, there is a sensitive dependence on initial conditions, meaning that different states of the system may be close initially, but will diverge exponentially over a short period of time. Assuming that this may be true, particular care should be taken in selecting tasks to be measured in conjunction with EEG acquisition. The introduction of different task related induced activity within the brain may affect subsequent results. As MF interactions may be somewhat dependent upon induced brain activity and not rest activity, future studies should utilize methods that take into account these sensitivities.

Another method of EEG analysis not yet undertaken in EEG-MF studies is that of wavelet analysis. This method has been most emphasized by Başar et al. [1999, 2000], particularly in the analysis of evoked related potentials (ERPs). ERPs are time varying signals that are superpositions of the different summated time courses of neural events occurring during stimulus processing. When the ERP waveform is averaged over multiple trials to increase the signal to noise ratio, it manages to only provide a rough estimate of the dynamic changes occurring in the brain. There are multiple, simultaneous processes that accompany ERP generation with different processes occurring over different brain areas and different time courses, ranging from milliseconds to seconds [Başar et al., 2001]. To assess the different contribution of these spatio-temporal variables to the ERP, the signal must be decomposed accordingly. Analysis by Fourier transformations masks temporal information of the neural events. Wavelet analysis is a better alternative for time frequency decomposition. The major advantage of wavelet analysis is that the ERP can be partitioned among several orthogonal functions (independent frequency components) with overlapping time courses at different scales [Yordanova et al., 2000; Demiralp et al., 2001]. The main advantage of this technique in studies of MF exposure would be in localizing possible subtle effects that may be occurring in the underlying neural activities that are obscured by other types of analysis.

States of awareness. An experimental direction not yet examined is the application of weak MFs to human subjects during altered states of awareness. This would include the induction of an altered state before, during or after exposure to investigate the role of active awareness upon human MF effects. An example of such an altered state might include hypnosis. Despite some dichotomous views regarding the nature of hypnosis [Spanos and Coe, 1992], there seems to be more evidence supporting the view that hypnosis is a specific, cerebral waking state, where the subject experiences vivid, mulitmodal, memory based imagery [Maquet et al., 1999]. Electrophysiological studies of hypnosis have found significantly reduced amplitudes of individual peaks in both the visual ERP [Jasiukaitis et al., 1996] and somatosensory

ERP in response to painful stimuli [De Pascalis et al., 1999].

A further reason for explorations into possible magnetic field effects upon altered states of awareness is the phenomenon of hypnotic analgesia. A number of neuroimaging studies of hypnotic analgesia have found a distinct pattern of activation and deactivation of cortical and subcortical regions [Rainville et al., 1999; Wik et al., 1999].

One of the most consistent effects of magnetic fields has been upon nociception [Kavaliers and Ossenkopp, 1993; Thomas et al., 1997a, for a thorough review see Prato et al., in press]. Animal studies of nociception have found significant relationships between MF exposure and analgesia [Kavaliers et al., 1998; Prato et al., 2000]. Kavaliers et al. [1984] established that exposure to a time varying ELF magnetic field (0.5 Hz, 0.2–0.4 mT) produced by rotating permanent magnets, which were originally used by Persinger et al. [1974] to produce behavioral, physiological and histological changes in developing rat pups, attenuated opioid induced analgesia in mice. This result was robust in their laboratory; and many publications followed, demonstrating that this effect could also be demonstrated for different strains of mice and different kinds of ELF fields, including 60 Hz [Kavaliers et al., 1994] and the pulsed ELF magnetic fields of magnetic resonance imaging [Prato et al. 1987]. Papi et al. [1992] and Del Seppia et al. [1995] reported effects consistent with magnetic field induced alterations in opioid function in homing pigeons. Papi et al. [1995] and Sartucci et al. [1997] also reported that sensitivity to painful electrical stimuli is increased in humans exposed to oscillating magnetic fields. The procedures that they used were consistent with magnetic field attenuation of stress induced, opioid mediated analgesia. In addition, Papi et al. [1995] demonstrated that an ELF exposure (-20–7 μT) may induce hyperalgaesia (increased sensitivity to a painful electrical stimulus) in humans.

The observation that earth strength ELF magnetic fields can attenuate opioid induced analgesia has been, with the exception of orientation and navigation effects, perhaps the most reliable and reproducible effect yet reported [Betancur et al., 1994; Del Seppia et al., 2000; Jeong et al., 2000]. If weak MFs have an effect upon nociceptive processing, it may well be of interest to explore its use in novel analgesic processing, such as hypnotic or placebo analgesia, particularly since opiate antagonist naloxone has been shown to attenuate MF-induced analgesia [Thomas et al., 1997a,b] as well as placebo analgesia [Amanzio and Benedetti, 1999; Amanzio et al., 2001]. MFs could also be used to augment or supplement the induction of hypnotic analgesia, as some previous studies have suggested [Tiller et al., 1994; Healey et al., 1996].

CONCLUSIONS

The pursuit of a unitary mechanism of interaction between MFs and biological systems has thus far yielded no conclusive evidence. However, studies of the phenomena associated with MF exposure are numerous. The reviewed EEG and cognition studies illustrate the remarkable variability in results when exploring the effects of MFs upon human brain activity. This makes it extremely difficult to draw any conclusions with regard to functional relevance for possible health risks or therapeutic benefits, a point recently noted by Voustianiouk and Kaufmann [2000]. Theoretical and experimental approaches have focused in large part upon the cellular and intracellular domain to investigate this phenomenon. Fewer experimental and theoretical ideas related to ‘coupling mechanisms,’ (i.e., the cascade of events which joins the initial biophysical mechanism by which tissue detects MFs to the precipitating neuronal and cognitive events) have come from a general systems approach examining large scale networks that mediate complex behaviors such as sensory integration and motor responses. Because ‘systems research’ addresses such a broad range of issues, it integrates experimental, analytic and theoretical techniques from a wide range of disciplines. Using such an approach, we can hopefully elucidate further evidence suggesting possible health risks or benefits associated with weak, ELF MF exposure.

ACKNOWLEDGMENTS

This research was funded, in part, by Canadian Institutes of Health Research, E. D. Hughes Mann, Lawson Health Research Institute, Plunkett Foundation, Fred Soyka Memorial Fund, FrAlex Therapeutics Inc., Ontario Innovation Trust, and Canada Foundation For Innovation.

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