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50 Hz Magnetic Field Exposure Influence on Human Performance and Psychophysiological Parameters: Two Double-Blind Experimental Studies

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Two double-blind studies were performed to examine magnetic field (MF) exposure effects and to determine the impact of temporal variation (continuous vs. intermittent exposure) of 100 μT_{rms} 50 Hz MF diurnal exposure on psychological and psychophysiological parameters in healthy humans. Three cephalic exposure sessions of 30-min, i.e., sham, continuous, and intermittent (15 s ON/OFF cycles) MF conditions, were involved. Each subject participated in all sessions, which were spaced at 1-wk intervals. In each session, mood ratings and performance measures were obtained before, during, or after exposure and several electrophysiological data (event-related brain potentials [ERP]) were recorded after each exposure session. These criteria were chosen to evaluate sensory functions as well as automatic and voluntary attentional processes. In experiment 1, 21 healthy male volunteers (20 to 27 years of age) were studied. Ten subjects were exposed at 13:30 h, and 11 subjects were exposed at 16:30 h. Statistically significant changes in the amplitude of ERP were observed after MF exposure in the dichotic listening task, indexing selective attention processes. Eighteen of the 21 original male volunteers took part in experiment 2, undertaken to better understand the results related to information processing involved in selective attention and control for ultradian rhythmicity. Exposure time for all the subjects was at 13:30 h. The analysis of the data again revealed significant amplitude changes of the ERP recorded in the dichotic listening task. Moreover, they demonstrated ERP latency and reaction time slowing in the oddball paradigm, a visual discrimination task after real MF exposure. These results also indicate that a low level 50 Hz MF may have a slight influence on event-related potentials and reaction time under specific circumstances of sustained attention. Bioelectromagnetics 20:474–486, 1999.

Key words: electromagnetic fields; mood; cognitive function; event-related potential (ERP); reaction time

INTRODUCTION

During the past 3 decades, scientific and public interest has focused increasingly on health effects to the human population of 50 or 60 Hz power-frequency magnetic field (MF). Failure to define precise mechanisms of interaction of these low intensity extremely low frequency (ELF) fields with living organism has resulted in a rapidly growing body of literature with diverging results and conflicts of data interpretation.

Some controlled laboratory studies have demonstrated subtle effects on human cerebral functioning, such as modifications of performances, alterations in the latency and amplitude of event-related potentials (ERP) and cardiovascular measures [see review, Crasson et al., 1992]. The main difficulty in identifying which function is electively affected by MF lies in the non-reproducibility of the results between and within laboratories. It is possible that differences in experimental design and procedures are responsible. But differences in variability associated with interindividual and intergroup differences have to be taken into account to highlight this absence of reproducibility and the observed diversity of results.

The general aim of our studies is to assess the psychological, psychophysiological, and neuroendocrine effects of low-intensity (100 μT_{rms}) 50 Hz MF

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exposure. Neuroendocrine data will be described in another paper (in preparation). We used various subjective, neuropsychological, and psychophysiological measures to clarify the precise nature of the psychophysiological functions affected by 50 Hz MF. Our research was organized in two stages. In the first stage, three general questions emerged: Is MF exposure susceptible to exert effects on mood and subjective feelings of vigilance which could interfere with performances? Does it exert an influence on the central nervous system that could be seen at a behavioral level, through such related performance measures as visual and auditive discrimination, selective attention, verbal learning, short-term memory, and psychomotor speed? Does MF exposure alter the central nervous system in a manner that involves modifications in the different perceptual and cognitive information processes expressed by the cerebral electrical activity, with or without behavioral changes?

The interest in electrophysiological measures is valid if we keep in mind that nervous activities are electrical and based on polarization-depolarization phenomena. Certain experimental data are accumulating concerning the influence of 50–60 Hz electromagnetic fields on spontaneous electrical activity [Bell et al., 1991, 1992; Lyskov et al., 1993 a, b] and cognitive ERP [Graham et al., 1990, 1994; Cook et al., 1992], which indicate influences on the cognitive processes of the brain (effect on the latter components of the waves) rather than in perceptive processes of afferent pathways. There are, however, few well-controlled studies that have conjointly, in the same experiment, assessed several psychophysiological parameters ranging from sensory functions to automatic and controlled, voluntary attentional processes to more clearly define which aspects of mental functioning and information processing are preferentially affected by MF exposure.

In the second stage, the question was raised whether the significant results obtained from the first experiment can be found in a second double-blind experiment undertaken under identical exposure protocol and in the same population to control for intergroup variability?

To examine MF effects (real exposure vs. sham exposure) and to determine the impact of temporal variable (continuous vs. intermittent MF exposure) of 100 μT_{rms} 50 Hz MF, the study population was submitted to three 30-min cephalic exposures: one sham condition and two real MF exposures (continuous and intermittent). We chose a field strength (100 μT_{rms}) similar to that in the proximity of some household and industrial electrical appliances.

EXPERIMENT 1

Material and Methods

Subjects Twenty-one (21) male subjects (1 left-handed and 20 right-handed), most of them university students, 20–27 years old (mean $\pm$ SD $= 22.7 \pm 1.8$ years), participated in this study. Each was offered a complete and accurate description of the aims, risks, and benefits of the study and was submitted to psychological (self-reported scales) and physical (medical and biological) examinations. A total of 29 subjects participated in the final screening; of these, four were excluded due to biological abnormalities (blood analysis) and one due to psychophysiological recording difficulties (recurrent difficulties in obtaining artifact-free recordings in the training session). One discontinued after the first exposure session because of anticipated anxiety and subjective complaints of concentration difficulties, hypersomnia, and excessive feelings of fatigue attributed to the MF exposure. Upon the opening of the exposure order codes, the subject had been sham exposed. The data of two subjects were deleted from the analysis when equipment problems invalidated 1 day of experiment.

The remaining 21 subjects completed all requirements, had normal hearing and normal or corrected-to-normal vision. Their general health was good (biological and medical examination), and they reported no history of chronic disease, neurologic and psychiatric illness, no medication use nor alcohol, drug, or tobacco (>20 cigarettes/day) abuse, and had no metal prosthesis or implants. They were instructed to eat balanced meals, not to drink alcohol, and to refrain from caffeine 24 h before and after each experimental day.

Exposure facility and procedures The exposure apparatus, a “magnetic helmet,” was specially designed by the University Department of Applied Electricity to expose the human head to maximally reduced electric fields and homogeneous 50 Hz MF. It is a cubic structure formed by six Helmholtz coils (35-cm diameter) distributed in the three orthogonal directions and sustained by a counterweight system (Fig. 1).

Each coil includes 350 turns in which sinusoidal 50 Hz currents up to 2 A flow, with each axis of the MF independently energized from an adjustable transformer. The control device allowed the operator to generate MF in the three orthogonal directions and an automatic time switch operated the temporal cycle, producing intermittent MF exposures. During this kind of exposure, the relay was operated every 15 s without any consideration of voltage or current zero-crossing. Therefore, some transients existed in the generated

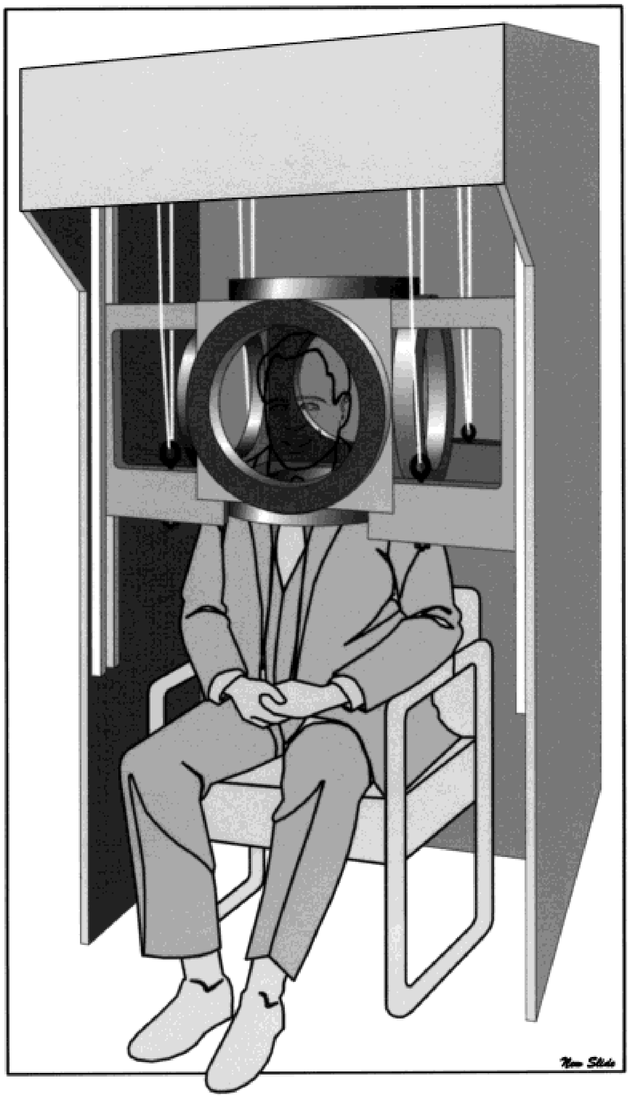

Fig. 1. Experimental design. The "magnetic helmet."

MF, although their magnitude was limited by the mainly inductive electrical circuit.

A screening study showed that this magnetic helmet did not produce perceptible warming or noise under experimental conditions [Crasson et al., 1993]. The double-blind strategy assumed that subjects were randomly assigned to exposure order and the field, controlled in intensity, direction, and duration, was manually generated by an operator not involved in this study and not present during the exposure and testing sessions. Immediately after each test session, subjects noted whether they thought that the fields were on or off during the exposure session and were asked upon which indices had they based their judgments. They noted their responses in a Field Status Questionnaire adapted to the French language [FSQ; Cook et al., 1992].

For real exposure sessions (continuous or intermittent), two pairs of coils were energized in phase to produce a uniform oblique 100 μT_{rms} 50 Hz MF, which, due to the physical installation of the apparatus, was parallel to the direction of the local geomagnetic field. The subjects were seated in the apparatus facing magnetic east. For the intermittent exposure condition, the generator was programed to produce 15-s ON/OFF cycles with the other characteristics identical to those of continuous exposure. In sham exposure, the field was off during the whole exposure session.

Ambient AC field strength in the experimental room was checked by using an EMDEX II (Enertech-EPRI) dosimeter and was ≤ 0.06 μT. Local geomagnetic field (DC field), measured with a Gaussmeter RFL912, was 40 μT at an inclination of 60° north. The horizontal component was 18 μT, and the vertical component was 32 μT.

Each subject participated in one training session and three weekly exposure sessions. The training session, intended to familiarize the subject with the techniques and material, was given 7 days before the experimental sessions. In this first experiment, 10 subjects were exposed at 13:30 h and 11 at 16:30 h (arrival time, a half hour before). Subjects were hospitalized for the night to collect blood samples for neuroendocrine measures (paper in preparation) in controlled-lighted rooms.

Measures D2-Attention test and three subjective state self-reports were performed immediately *before* and *after* exposure sessions, either before (D2) or during (self-reports) attachment of the electrodes.

Two memory tasks were performed *during* exposure: the Rey Auditory Verbal Learning Test (10 min after exposure began) and the Digit Span (at minute 20). Six electrophysiological recordings were made immediately *after* each 30-min exposure session. The electrophysiological recordings were chosen to evaluate sensory functions (visual evoked potential [VEP]) as well as automatic (mismatch negativity [MMN] paradigm), controlled and voluntary attentional processes (dichotic listening task [Nd], visual and auditory oddball and contingent negative variation [CNV] paradigms). Some included performance measures (accuracy evaluation and reaction time).

Subjective Measures

Visual analogue scales [VAS, Norris, 1971], the Profile of Mood States [POMS, Mc Nair et al., 1971], and the State version of the State-Trait Anxiety Inventory [STAI, Spielberger et al., 1970] were used to assess mood and subjective vigilance feelings.

Performance and Electrophysiological Measures

The *D2-Attention* test [Brinckenkamp, 1962] is a paper-and-pencil instrument in which the subject must mark each occurrence of a target symbol in each of 14 lines of symbols of similar appearance. Twenty seconds are allotted for each line. Total score including marked signs, error frequency, omissions, and false alarm as well as the variability of performance were analyzed.

The *Rey Auditory Verbal Learning Test* [Rey, 1964] consisted of a list of 15 spoken words that the subject must recall within five trials. In the second part of the test (contextual memory), the subject must recognize the memorized words in a story. After the exposure time and the electrophysiological recordings, a delayed recall task of these words was required. Total words memorized, number of errors, and number of words repeated during the story and in the delayed recall condition were calculated and compared in the three experimental conditions.

The *Digit Span* is a classic memory subtest extracted from the Wechsler Adult Intelligence Scale [1955]. This test requires subjects to recall numerical series of increasing length, either forward or backward. Performance was evaluated in terms of the total numbers correctly recalled (maximum 17).

In order of their administration, the electrophysiological recordings were The *Visual Evoked Potential (VEP), Mismatch Negativity (MMN), dichotic listening task (Nd), P300 wave,* and *Contingent Negative Variation (CNV)* test. The *VEP paradigm*, in which stimuli were 60 transient checkerboards lasting for 100 ms, displayed binocularly on a video screen and delivered with a 1-s interstimulus interval (ISI). The subjects were seated in a chair 1.20 m from the screen. They were instructed to fix upon a cross located in the center of the screen. Electroencephalographic (EEG) data were recorded from left and right occipital locations (O1, O2; according to the 10–20 system) referenced to the midfrontal region (Fz), by using Ag-Cl cup electrodes, with a time constant of 1 s. They were digitized at a sampling rate of 128 data points for 500-ms epochs that included 100 ms of prestimulus activity. The latency and amplitude of the four main components (N1-P1-N2-P2) were measured off-line, by using cursor markers, in relation to the referred prestimulus period.

Automatic processing was explored through the *MMN paradigm* [Näätänen, 1992]. The MMN is a change-specific negativity elicited by deviations in auditory stimuli which appears 100 to 250 ms after stimulus onset. Standard stimuli consisted of tones of 40 ms (800 Hz, 64 dB SPL, 5 ms rise/fall (R/F) time, $n = 175$), whereas the deviant stimuli were tones ($n = 25$) differing only in duration (80 ms). The ISI was constant at 800 ms (onset to onset). The subjects were instructed to ignore the tones and to concentrate on a visual attention task ("Test du Compteur de Tours;" Rey). EEG data were recorded with a time constant of 1 s from frontal (Fz), central (Cz), and parietal (Pz) locations referenced to linked ear lobes and digitized at a sampling rate of 256 data points per 750-ms epoch, which included 150 ms of prestimulus activity. MMN was calculated as the difference of waveforms between the standard and deviant stimuli evoked potentials. Two measurements were made, the first within the 80- to 120-ms after stimulus onset and the second within the 140- and 250-ms range.

Selective attention was explored through a *dichotic listening task* [Hillyard et al., 1973]. Selective attention is defined as the process by which the perception of certain input in the environment is enhanced, whereas that of other concurrent stimuli is relatively suppressed. The earliest effect of attention observed in the human auditory ERP was a negative wave elicited by attended stimuli relative to the ERP elicited by nonattended stimuli [Hillyard et al., 1973; Hansen and Hillyard, 1980; Näätänen, 1992]. This negative difference, called Nd, frequently overlaps the sensory evoked N1 component, which peaks at about 100 ms.

In our psychophysiological paradigm, four types of stimuli were delivered via stereo headphones. The nontarget or standard stimuli ($P = 0.90$) were 800 Hz tones for the right ear ($n = 180$) and 1500 Hz tones for the left ear ($n = 180$). The target stimuli ($P = 0.10$) were 840 Hz tones for the right ear ($n = 20$) and 1560 Hz tones for the left ear ($n = 20$). All these stimuli had an R/F time of 2 ms, an intensity of 70 dB SPL, and a 50-ms duration. The sequential order of presentation of tones to right and left ears was randomized, as were the time intervals between successive tones (ISI, 350–850 ms) and the occurrence of target tones within each channel. Subjects were instructed to attend to, detect, and count the occasional targets from standard tones in one ear and to ignore the other ear or channel. The task was divided in two subtests with a counterbalancing order of presentation for right (Attend-Right condition) and left (Attend-Left condition) ear attention focusing condition over session. This task is made deliberately difficult to ensure that the subject had to attend very closely to all the tones in the designated ear.

EEG data were recorded from Fz, Cz, and Pz locations referenced to linked ear lobes with a time constant of 1 s and digitized at a sampling rate of 128 data points per 250-ms epoch which included 50 ms of prestimulus activity. The data were averaged on line according to stimulus category. The ERP components were assessed as averaged voltages within specified time windows: N1 (80- to 120-ms latency range) and N2 (120- to 240-ms latency range), referred to the mean voltage of the prestimulus period. Two other measures were calculated as the difference of waveforms between attended and nonattended stimuli evoked potentials: the Nd1 (80–120 ms) and Nd2 (120–240 ms). As described in the literature, the analysis focused on the EEG data obtained for standard tones: attended vs. unattended channel [Näätänen, 1992]. Quality of discrimination was evaluated in percentage of correct responses.

The *P300 wave* is the most extensively studied cognitive ERP component. Task-relevant sensory stimuli (targets) that allow subjects to make a decision elicit a P300 or positive component with a modal latency of 250–400 ms [Sutton et al., 1965, 1967; Donchin, 1979]. Active attention toward the target signals of the cognitive task (with or without motor response) is necessary for enhancing P300. The latency of this wave is linearly related to task complexity, whereas its amplitude, maximal at centroparietal scalp locations, is related to the subjective probability (depending on the frequency of a stimulus and the sequential structure of the stimulus series) and to the stimulus meaning (nature of the situation or task) [Johnson, 1986]. The P300 is typically obtained by a so-called *"oddball" task* in which the subject must rapidly and accurately respond with a key press after each occurrence of the less probable (oddball or target) of two stimuli. The targets ($n = 60$) were randomly intermixed in a long series of nontarget stimuli ($n = 240$). The task was presented in the auditory and visual modality. In the *auditory* modality, nontarget stimuli were 800 Hz tones (70 dB, 5-ms R/F time, 40 ms) delivered binaurally to the subject via headphones, whereas targets were higher pitched tones (1470 Hz). In the *visual* modality, nontarget stimuli consisted of the letter "X" presented for 100 ms in the center of a video screen, whereas targets were the letter "O." All the stimuli were delivered with a constant ISI (1 s).

EEG data were recorded from Fz, Cz, and Pz locations referenced to linked earlobes with a time constant of 2 s and digitized at a sampling rate of 256 data points for 600-ms epochs that included 150 ms of prestimulus activity. Latency and amplitude of P2, N2, and P3 peaks were measured off line, by using cursor markers, for target and/or nontarget stimuli in relation to the prestimulus baseline. Reaction time was recorded for each target.

The *CNV test* [Walter et al., 1964] is a slow negative shift after a warning stimulus (S1), which prepares the subject to respond to a second (imperative) stimulus (S2). This wave has a widespread anteroposterior and bilateral distribution [for review, see Timsit-Berthier, 1984]. A 50-ms tone warning stimulus was followed 1 s later by a second tone of 100 ms (S1 & S2: 1000 Hz, 70 dB SPL, 5-ms R/F time). The subject had to respond to S2 by pushing a button. The stimuli presentations were separated by intertrial intervals ranging from 7 to 25 s. Subjects were instructed to keep their eyes closed during the recording session to minimize artifact. EEG data were recorded from Fz, Cz, and Pz locations referenced to linked earlobes with a time constant of 5 s and digitized at a sampling rate of 512 data points for 4000-ms epochs that included 1000 ms of prestimulus activity. Slow wave amplitudes were measured by computing on 32 artifact free waves the average amplitude over each of the three latency ranges: two intervals in the S1-S2 epoch (500–700 ms and 800–1000 ms after S1) and one after the S2 (500–700 ms after S2). Reaction time was recorded for each response.

For all recordings, subjects were seated in a sound attenuated, air conditioned, and electrically shielded room, installed inside the laboratory, and were instructed to refrain from eye movement, blinks, or other bodily movements during the recordings. The vertical electro-oculogram (EOG) was recorded. Epochs exceeding peak to peak thresholds of 100 μV at any electrodes were rejected as containing extracerebral artifacts. Data were processed by a specially designed software (INSTEP SYSTEMS, Ottawa, Canada).

Statistical Analysis

The statistical analysis was carried out by a repeated measure analysis of variance (ANOVA-R) conducted to test the effect of exposure conditions. When significant results emerged, post-hoc analysis was undertaken to determine between the sets of conditions that were statistically different. Differences were considered statistically significant if their probability was 0.05 or less. The χ^2 test was used to analyze FSQ data. Additional ANOVA were computed with the order level as between-subject factors to check the effectiveness of the counterbalancing procedure and to remove any variance due to practice. The three order levels were A-B-C, C-A-B, and B-C-A for which A is the sham condition, B the continuous exposure, and C the intermittent.

Results

Statistical analysis of the Field Status Questionnaire shows that subjects were unable to perceive the presence of the MF in the helmet ($P = 0.7$, $\chi^2 = 2.20$, $df = 4$). Correct judgments composed 25% of the observations, whereas 54% were incorrect judgments. Twenty-one percent (21%) of judgments indicated the subject was uncertain.

Subjective measures No significant field-related effects were found on subjective ratings of mood (STAI-State, POMS) or vigilance (VAS, POMS).

Performance and electrophysiological measures The performance measures, reaction time included, did not vary between the three experimental conditions. In each condition, subjects maintained a high level of performance with rapid reaction times, more rapid in the auditory (auditory P300 paradigm) than in the visual modality (visual P300 paradigm) and faster when a warning stimulus prepared the subject to respond (CNV paradigm). These data support the data generally described in the literature.

In the dichotic listening task, one of the six EEG recordings, significant differences between field conditions were observed. These differences were seen in the frontal and parietal scalp locations and early part of the wave development (N1 and Nd1).

The differences observed in the frontal regions mainly distinguished the two real exposure conditions. Compared with the continuous MF exposure condition, there was a decrease of the N1 amplitude measured in the "Attend-Left condition" after the intermittent exposure. This decrease was observed for the N1 evoked by left ear attended stimuli ($P = 0.02$, $F = 4.19$, $df = 2, 62$) and for the N1 evoked by right ear nonattended stimuli ($P = 0.04$, $F = 3.55$, $df = 2, 62$). Moreover, the post hoc analysis indicated that the N1 decrease of amplitude observed for the left ear attended stimuli differed not only between intermittent and continuous exposure but also between intermittent and sham exposure. This finding is not the case for the N1 amplitude evoked by right ear nonattended stimuli, differing only between the two real MF exposure conditions. There was also a decrease of the Nd1 amplitude evoked by the left ear delivered stimuli after the intermittent exposure compared with the continuous exposure ($P = 0.049$; $F = 3.25$; $df = 2, 62$; mean difference, 1.10 µV). Figure 2 shows dichotic listening task mean N1 amplitude measured in the three recording sites (Fz, Cz and Pz) in the three experimental conditions.

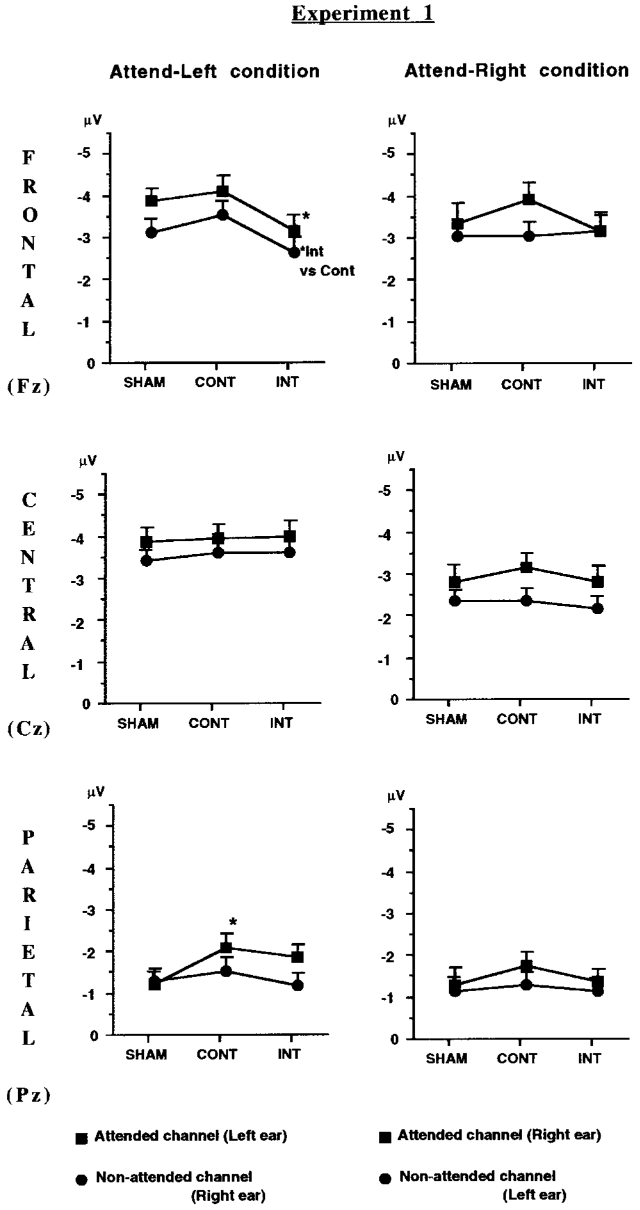

Fig. 2. Experiment 1. Dichotic listening task. Mean amplitude (±SEM) of the N1 recorded in frontal (top), central (center), and parietal (bottom) sites and in the three exposure conditions (sham, continuous MF exposure, and intermittent MF exposure). The left side of the figure represents Attend-Left condition data, and the right side represents Attend-Right condition data. * $P < .05$.

Another difference was observed in the parietal region between sham and real field conditions, but without affecting the Nd. The amplitude of the N1 wave recorded in the parietal site for the attended left ear stimuli was significantly higher after continuous MF exposure than after sham field condition ($P = 0.03$; $F = 3.82$; $df = 2, 62$; mean difference, 0.89 µV). This effect is not related to any order or exposure period interaction.

This is not the case for the results obtained in the frontal region. Reactivity differences were seen between the 13:30 h and the 16:30 h groups. Statistical interaction analysis indicated that, unlike the 16:30 h group, subjects exposed at 13:30 h presented a reduced amplitude of the Nd1 Fz obtained for left ear stimuli after intermittent exposure compared with the other two conditions ($P = 0.002$, $F = 9.62$, df = 2, 14). This difference is linked to a higher N1 amplitude after intermittent exposure compared with the other two conditions for the left ear stimuli, which have to be ignored in the Attend-Right condition ($P = 0.01$, $F = 5.78$, df = 2, 14). Moreover, the task was more difficult for the 13:30 h group, which showed a much higher percentage of error the first time the test was taken (Attend-Right condition) (mean ± SEM = 138 ± 62% vs. 13 ± 7% for the 16:30-h group, field by order by exposure moment interaction: $P = 0.03$, $F = 3.87$, df = 2, 38).

Differential reactivity between the 13:30 h and 16:30 h groups also emerged in two other tasks. The first is related to the amplitude of the P300 component obtained in frontal region (Fz) in the auditory oddball task. This component is enhanced after continuous exposure in the 13:30 h group, whereas reduced in the 16:30 h group relative to the sham exposure amplitude ($P = 0.03$, $F = 3.97$, df = 2, 34).

The second significant interaction between exposure time and field condition is related to the N1 amplitude evoked by the warning stimulus (S1) in the CNV recording, which is reduced in the 13:30 h group after intermittent exposure in the vertex (Cz) and after continuous exposure in the parietal region, whereas enhanced in the 16:30 h group, relative to the sham condition N1 amplitude (pCz = 0.008, $F = 5.61$, df = 2, 34 and pPz = 0.04, $F = 3.62$, df = 2, 34).

EXPERIMENT 2

In a field of research in which results cannot be easily reproduced, the question of intergroup and interindividual variability is of major importance. The first experiment led us to recognize some methodological improvements, leading toward a better understanding of which specific aspects of mental functioning is electively affected by MF exposure and under which conditions MF effects may appear. We decided to maintain a series of parameters concerning, first, the choice of MF exposure characteristics and, second, the choice of the population, to control for exposure characteristics specificity and intergroup variability.

Because selective attention was the most sensitive process affected by MF exposure in the first experiment, it was appropriate to also investigate this function in the visual modality to test the modality-dependent sensitivity hypothesis. The memory tests presented during exposure session were also replaced by a so-called "stress-test," a version of the Stroop Color-Word test, presented during the last 13 min of exposure. Moreover, some improvements were made in the recording of the dichotic listening task ERP. They involved ear/frequency of stimulus distinction, addition of recording sites, and further training before experimental sessions for the subjects who had discrimination difficulties in the former study. Because the 13:30 h group appeared more sensitive than the 16:30 h group, we decided to control for ultradian rhythmicity by exposing all the subjects at 13:30 h.

Material and Methods

Subjects Eighteen of the 21 male volunteers who participated in the previous experiment took part in the second experiment, undertaken 18 months later. They were resubmitted to psychological (self-rating scales) and physical (health questionnaire) examinations to ensure the absence of a psychological or medical problem.

Exposure facility and procedures The exposure facility and the apparatus designed to drive the coils and record subjects responses were identical to those in the first experiment. Procedures for the three exposure sessions followed those described in the first study, in accordance with the double-blind design. The same adapted field status questionnaire [Cook et al., 1992] was used to verify that the subjects cannot perceive the MF.

Measures Two subjective state self-reports were obtained *before* and *after* each session (during electrode placing). The visual selective attention task with reaction time recording (Stroop Color-Word test) was performed *during* exposure. Three psychophysiological paradigms (dichotic listening task, visual oddball, and CNV paradigms) were recorded immediately *after* the 30-min exposure sessions. They included performance measures (accuracy evaluation and reaction time measures).

Subjective measures The two subjective state measures taken in this study were the Visual Analogues Scales and the State version of the State-Trait Anxiety Inventory (STAI) described in the first experiment. The recently revised version of the STAI (Form Y) was used [Spielberger, 1993].

Performance and electrophysiological measures The *Stroop Color-Word* test [Stroop, 1935] has become, since its introduction 60 years ago, one of the most widely used tests of visual selective attention. We used a modified method of mixing neutral stimuli within congruent and incongruent stimulus sets in a computerized reaction time version. Stimuli, single words printed in colored ink, were presented in the center of the monitor screen, with responses made on the keyboard and reaction times recorded with millisecond accuracy. Presented in random order, the stimulus was a color-congruent word (RED printed in red [n = 50] or BLUE printed in blue [n = 50]) a neutral word (DOG printed in red [n = 50] or in blue [n = 50], CAT printed in red [n = 50] or in blue [n = 50]), or a color-incongruent word (RED printed in blue [n = 50] or BLUE printed in red [n = 50]). The task was to respond to the relevant dimension (color) while ignoring the task-irrelevant information (word) and to touch the corresponding keyboard letter (letter R for red and B for blue). Reaction time and accuracy were calculated for each category of stimulus.

Results from previous experiments led us to choose three of the six previous electrophysiological paradigms: the dichotic listening task, which showed significant differences, the visual oddball paradigm (P300), which indicated interindividual reactivity [Crasson, 1995] (Hedonic subjects [Scale for Physical Anhedonia, Chapman et al., 1976] appeared to be more reactive to the MF exposure than anhedonic subjects), and the CNV, which it is a psychophysiological paradigm related to attention, motivation, and motor preparation and particularly sensitive to arousal fluctuations [Tecce, 1972].

In the dichotic listening task, standard tones were still 800 Hz and 1500 Hz because target tones were 840 Hz and 1560 Hz, respectively, as in the first experiment. The task was divided in 2 × 4 subtests with a counterbalancing order of presentation for right and left ear attention focusing condition and for tonal-frequency of stimuli: 2 Attend-Right subtests with 800/840 Hz right ear delivered tones as attended stimuli (subtests 1 and 7), 2 Attend-Right subtests with 1500/1560 Hz tones as attended stimuli (subtests 4 and 6), 2 Attend-Left subtests with 800/840 Hz left ear delivered tones as attended stimuli (subtests 3 and 5) and 2 Attend-Left subtests with 1500/1560 Hz tones as attended stimuli (subtests 2 and 8). The distinction between ear-specific and stimuli frequency effects would be helpful in distinguishing between hemispheric differentiation–related effects (left ear–specific effect would involve the right hemispheric–specific process) and physical characteristics of stimuli-related effects (involving particular degree of task difficulty, for instance). The earlier results showed complex statistical interactions in the midfrontal site. To clarify this aspect, we added two recording sites in this region. ERP were recorded from left (F3) and right (F4) frontal region in addition to Fz, Cz, and Pz recording sites.

Results

Subjects were unable to detect the presence of the field in the helmet ($P = 0.9$, $\chi^2 = 1.19$, df = 4). Regarding the field status, 31% of the observations made was correct, 54% was incorrect, and 15% was indecisive.

Subjective measures As in the previous study, no significant field-related effect was found on subjective ratings of mood and vigilance.

Performance and electrophysiological measures Performances of the Stroop Color-Word test (reaction time and accuracy measures), during exposure sessions did not differ between experimental conditions, whatever the type of stimuli suggested (congruent, incongruent, or neutral).

Significant differences were obtained in the dichotic listening and visual oddball paradigms. Those observed in the dichotic listening task are related to the central and parietal recording sites. They indicated a significantly higher amplitude of the N1 for the attended right ear stimuli after continuous exposure than after sham condition in the central region ($P = 0.01$, $F = 4.94$, df = 2, 53). The same enhancement occurred in the parietal region between the MF exposure (continuous and intermittent exposure) and sham condition ($P = 0.008$, F = 5.63, df = 2, 53). Order of exposure did not interact with these variables. In the central site, the amplitude difference is 0.61 μV, whereas in parietal site, they are 0.76 μV and 0.55 μV (for continuous and intermittent vs. sham condition, respectively).

Indeed, differences observed in the attended stimuli evoked potentials were not reflected in Nd amplitude measures between attended and nonattended stimuli evoked potentials. Moreover, no difference was observed between experimental conditions when the same analyses were carried out with the frequency of stimuli (1500 Hz vs. 800 Hz) delivered as a dependent variable (when left ear and right ear stimuli are pooled together). Finally, no difference was present in the frontal areas (Fz, F3, or F4). Figure 3 represents dichotic listening task mean N1 amplitude recorded in the mid-frontoparietal line (Fz, Cz, Pz) in the three experimental conditions.

During the second recording, of the visual oddball paradigm, reaction time was significantly slower after continuous MF exposure (mean ± SEM = 364 ± 7 ms) than after sham exposure (mean ± SEM = 348 ± 9 ms, $P = 0.038$, $F = 3.60$, df = 2, 53). The difference was 16 ms. RT was not different when continuous and intermittent exposure were compared (Fig. 4). Table 1 indicates the mean reaction time values obtained in the two experiments.

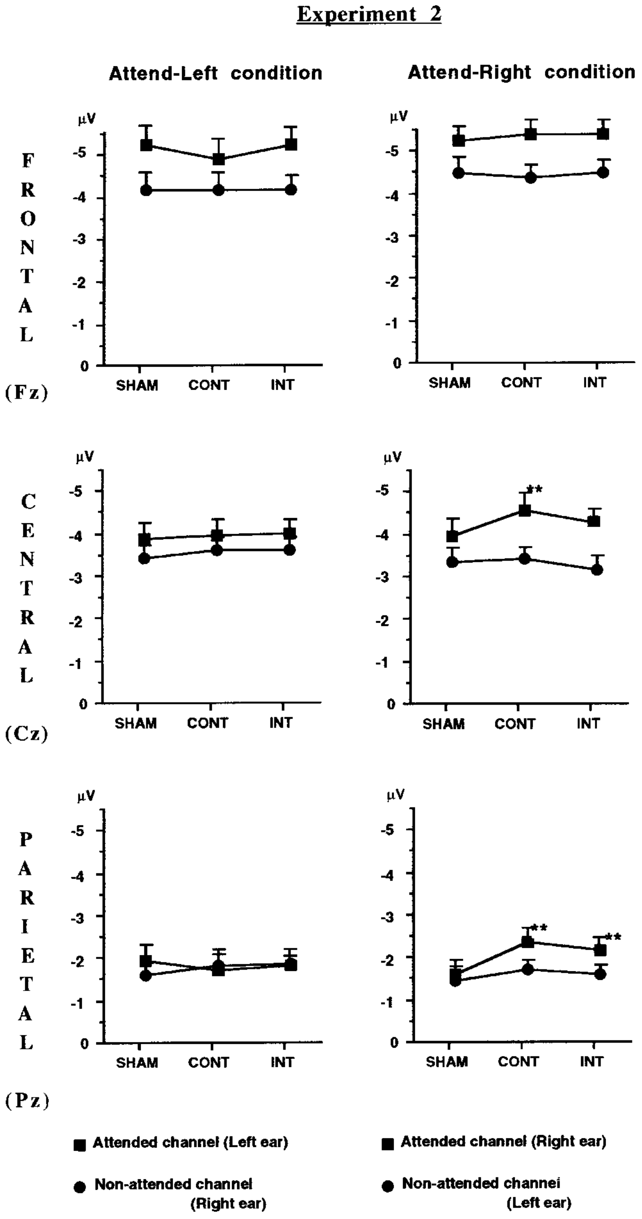

Fig. 3. Experiment 2. Dichotic listening task. Mean amplitude (±SEM) of the N1 recorded in frontal (top), central (center), and parietal (bottom) sites and in the three exposure conditions (sham, continuous MF exposure, and intermittent MF exposure). The left side of the figure represents Attend-Left condition data, and the right side represents Attend-Right condition data. ** $P < .01$.

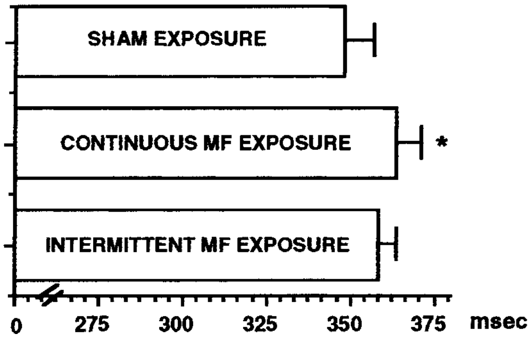

Fig. 4. Experiment 2. Visual oddball paradigm. Mean reaction time (±SEM) in the three magnetic field exposure conditions. * $P < .05$.

TABLE 1. Visual Oddball Paradigm Reaction Time

Experiment	Sham condition	Continuous MF exposure	Intermittent MF exposure
Experiment 1	362 (6)	362 (4)	264 (5)
Experiment 2	348 (9)	264 (7)*	358 (6)

* $P < .04$. Mean reaction time (and SEM) in the three magnetic field exposure conditions n = 2 (experiment 1) and 18 (experiment 2).

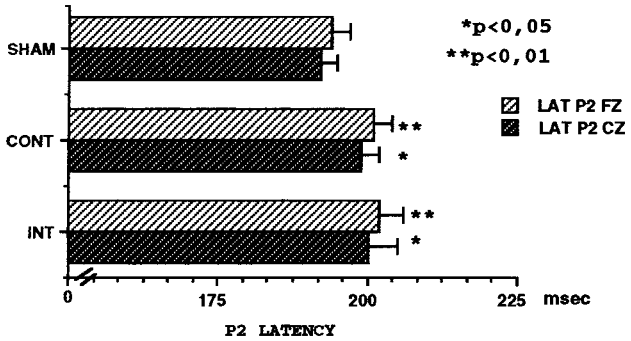

Fig. 5. Experiment 2. Visual oddball paradigm. Mean P2 latency (±SEM) recorded in two derivations (Fz and Cz) in the three magnetic field exposure conditions: sham condition (top), continuous MF exposure (center), and intermittent MF exposure (bottom) conditions. * $P < .05$; ** $P < .01$.

When latencies and amplitude of the evoked potentials were considered, there was no significant field-related amplitude or latency change in any site in the N2 or P300 amplitude or latency. But the P2 latency for target stimuli was longer after MF exposure than sham condition in two recording sites (Fz: $P = 0.01$, $F = 5.27$, df = 2, 53; Cz: $P = 0.018$, $F = 4.51$, df = 2, 53). The slowing is about 8 ms after continuous exposure and 7.5 ms after intermittent exposure (Fig 5). Statistical analysis failed to reveal significant field-related differences in the evoked potentials or in the reaction time measures obtained in the three CNV recordings.

DISCUSSION

In these two studies, diurnal short-term (30 min) 100 μT_{rms} 50 Hz MF exposure of the human head results in some modifications of the amplitude of ERPs recorded in the selective attention task (experiment 1 and 2) and conjointly in latency and reaction time changes in the signal detection task (experiment 2). They are original in that they control the interindividual variability with the choice of a double-blind design and control the intergroup variability in performing them with the same group of volunteers. Moreover, they conjointly assess different cognitive processes through various measures of mood, performance, and ERPs. If they indicate that 50 Hz 100 μT_{rms} magnetic field exposure can influence human psychophysiological processes, the observed differences between real and sham exposure are few, subtle, transitory and seemed to be specific to some aspects of cognitive functioning. They are independent of field perception. These results are in agreement with existing laboratory data related to the absence of MF exposure effect on self-reported mood, often measured through self-reported scales like VAS, MACL, or POMS [Beischer et al., 1973; Sander et al., 1982, 1986; Graham et al., 1984, 1990, 1994; Cook et al., 1992].

Performance measures indicate an absence of MF exposure influence on memory processes and discrimination capacity indexed by the various quality measures (missing, false alarm, total error number in the visual and auditory oddball paradigms, D2-Attention test and Stroop test, errors percentage in the dichotic listening tasks). Memory tasks do not show direct (during exposure) or indirect (delayed evocation) MF influence on memorization. These data do not support the Lyskov hypothesis [Lyskov et al., 1993a] concerning the influence of intermittent MF exposure on associative and long-term memory processes. Moreover, the absence of MF effects on short-time memory span, indexed by the Digit Span task and demonstrated in the Midwest Research Institute (MRI) studies with combined electric and MF and multiple intensities (6-9-12 kV/m, 10-20-30 μT), is replicated here in exposure conditions with the magnetic component isolated from the electrical component [Graham et al., 1990; Cook et al., 1992]. We also did not find the concentration capacity disturbances observed in the D2-Attention test in our pilot study in which two groups of subjects, one real and one sham exposed, were compared [Crasson et al., 1993]. These data support Sander's results obtained with high intensity 50 Hz electrical (20 kV/m) or magnetic (5 mT) field exposure [Sander et al., 1982, 1986].

Some questions arise from the reaction time results. Whereas there was no difference between exposure conditions in the three reaction time measures in the former study (auditory and visual oddball tasks and CNV recordings), a reaction time slowing was observed after MF exposure in the visual oddball task of the second experiment. This reaction time slowing occurred after the exposure session, after a long period of sustained attention to a series of cognitive tasks, some of them also including reaction time measures (Stroop test). Although mean reaction time between experiment 1 and experiment 2 seemed shorter after sham and intermittent conditions in experiment 2 (Table 1), indicating some learning effect absent in continuous MF exposure, the difference was not statistically significant. Moreover, there was an absence of correlation between test-to-test mean oddball reaction time. This could be interpreted in the context of several sources of variation related to, for instance, the possible choice of alternative strategies to cope with the variation of mental load required by the tasks in the two experiments and with the level of fatigue of each subject. Practice effects from the first test session and the intraindividual changes that may have occurred during the long interexperiment interval may have led to greater variability as well.

It is difficult to draw any conclusion from the divergent results found in the literature, which at different times indicated decrement, improvement, or no effect of ELF electromagnetic field exposure on reaction time speed in various experimental designs [Friedman et al., 1967; Beischer et al., 1973; Hauf, 1976; Silny, 1981; Stollery, 1986; Teresiak and Szuba, 1989; Graham et al., 1990, 1994; Cook et al., 1992; Lyskov et al., 1993 a,b; Podd et al., 1995]. With similar visual and auditory detection signal tasks (oddball paradigms), the MRI studies referred to a reaction time decrement observed with the auditive paradigm in the lower electric and MF exposed group (6 kV/m, 10 μT), a slight reaction time improvement with rapidly alternating intermittent fields (9 kV/m, 20 μT, 8 × 45 min ON/OFF MF exposure periods with 15-s ON/OFF switching) and no MF effect in two other experiments [Graham et al., 1990, 1994]. Recently, Whittington and Podd [1996] observed that 50 Hz, 100 μT_{rms} intermittent MF exposure speeded reaction time, with a difference of 14 ms when the task changed from the easiest to the most difficult level. They concluded that even though they removed the confounders involving both task and difficulty level changes, "it is still not clear from our results whether field exposure affects a particular range of RT values or whether the actual task itself is the important factor."

If our experiments focused on the same characteristics of MF exposure (50 Hz, 100 μT_{rms}), there are some potentially important differences between these two double-blind studies: the nature and the difficulty of the task (relatively difficult duration-discrimination task in the Whittington study vs. easy pitch-discrimination task), the mode of the MF exposure, in particular the intermittency (1-s vs. 15-s ON/OFF cycles) and the exposure duration (9 min vs. 30 min). There are many "minor" but also potentially relevant differences lying in exposure condition (geomagnetic orientation field strength and orientation, ambient AC MF strength, exposure moment, MF orientation, exposure apparatus, etc.) and in the population studied (number of subjects, age, standard deviation, etc.). But do they explain why the reaction time at various times increased, decreased, or remained constant? Further systematic studies are necessary to determine which parameters contribute to the understanding of MF behavioral effects.

The electrophysiological data did not diminish the problem complexity. Our two studies support previous experimental data related to short-latency or exogenous potential recordings showing that 50–60 Hz electromagnetic fields of this strength range have no replicable effect on conduction velocity and neural transit time of visual or auditory information to the cortical projection areas [Sander et al., 1982, 1986; Graham et al., 1992; Lyskov et al., 1993a]. MF exposure does not alter the amplitude and latency of the exogenous VEP components in experiment 1 and of the early part of nontarget stimuli evoked potential in the oddball paradigm (N1 and P2) in experiment 1 and 2. The use of ERP or endogenous potentials provides a means of measuring cognitive processing and reflecting processes that occur between the stimulus and the response during attention tasks.

A number of components have been well documented and linked to different mental processes, including early feature analysis and attentional gating (N1, Nd), sensory mismatch detection (mismatch negativity [MMN]), stimulus discrimination (N2), completion of stimulus evaluation, cognitive closure, or context updating (P300). The contingent negative variation (CNV), which has various subcomponents and was the last task presented to the subjects after each experimental condition, has been related to different mental states and activities, including expectancy, motivation, arousal, and attention. Most of these components are unchanged after real MF exposure, compared to the sham condition, as shown by the various test protocols designed to evoke them.

In the first experiment, however, we observed in the dichotic listening task an amplitude rise of the N1 evoked by the attended stimuli after MF exposure compared with sham condition (Attend-Left condition, Pz). An amplitude rise of the N1 evoked by the attended stimuli was also shown in the second experiment (Attend-right condition, Cz, Pz). Despite some existing analytical data related to interhemispheric and interaural differences in the human auditory evoked potential [Peronnet and Giard, 1980; Giard et al., 1987], the observed alternations between right ear and left ear effects in the two studies make any differential hemispheric MF action explanation difficult and precocious. Moreover, the differences observed in the frontal regions (Fz) were not found again in the second experiment, in which interindividual differences in the capacity to perform the task, task difficulty, and ultradian rhythmicity (13:30 h vs. 16:30 h) were controlled.

Although EEG changes occurred in the dichotic listening task, the effects on the physiological system observed in the two studies may not have been great enough to be exhibited in the negative difference (Nd) between attended and unattended stimuli evoked potentials or at a behavioral level (quality of performance). Moreover, these changes were all well within the normal ranges obtained by using these measures.

But, in the second experiment, dichotic listening changes are followed in the oddball task by a latency increase of the P2 component evoked by target stimuli after MF exposure, which is accompanied by the slowing of reaction time discussed above. P2 is a sensory-related component, but for the target evoked waves, it seems to be related to the initiation of the primary processes of stimulus identification and classification of response selection attributed to the N2 component that follows it [Lembreghts et al., 1995].

We did not find in the oddball tasks the amplitude and/or latency modifications of nontarget stimuli evoked potentials obtained nor those observed in the latest part of the target stimuli evoked potential (N2 and P3) in the MRI studies [Graham et al., 1990]. Despite the same type of task use (oddball paradigm with reaction time measure), there are major differences in the electromagnetic field parameters chosen between the two team experiments (combined electric and magnetic field exposure of lower intensities in Graham et al. studies) and in the time of recording (also during exposure in the Graham et al. studies).

Regarding MF parameters, our data do not support other reports which suggest that intermittent exposure might be more effective than continuous exposure [Graham et al., 1990; Cook et al., 1992; Lyskov et al., 1993b]. Except for the dichotic listening differences observed in frontal derivations in experiment 1, in which task difficulty and ultradian rhythmicity might interfere with possible MF influence, statistically significant differences occurred more often between continuous MF exposure and sham condition than between intermittent MF exposure and sham condition. The N1 amplitude enhancements for attended stimuli in the dichotic listening task were obtained after continuous exposure in experiment 1 (Pz location) and experiment 2 (Cz and Pz). P2 latency (Cz and Pz) and reaction times were slowed after continuous exposure in experiment 2. The less frequently obtained differences after intermittent MF exposure were always in the same direction as those after continuous exposure (N1 amplitude enhancement in the dichotic listening task of experiment 2 (Pz only) and P2 latency slowing [Cz and Pz]). It should also be noted that the intermittent condition in the present study contained magnetic field transients, whereas the previous studies did not. However, this fact does not explain why continuous exposure, during which no transient is present (the MF were switched on and off in the absence of the volunteer), seems to be more effective.

Further studies are needed to test other durations of exposure and other intermittency formats. Given the small number of studies in this area, it is not only necessary to examine other exposure conditions but also to examine conjointly and systematically which neurophysiological and behavioral parameters are selectively affected by MF exposure. It is also necessary to determine in which conditions and under which parameters of exposure to MF effects become visible. Moreover, the vulnerability question often cited in the field of ELF MF exposure has to be investigated through the systematic search of criteria, allowing the identification of persons more sensitive to this type of exposure.

CONCLUSION

These studies indicate that 30-min diurnal, 100 μT_{rms} magnetic field exposure might alter the psychophysiological processes involved in a specific type of cognitive processing, conditioned by the active mobilization of attentional capacity, by a high mental load and by its own nature, which suggests filtering and activation processes involved in selective attention. These effects appeared more markedly and were accompanied by slower processing and sensory-motor speed in a relatively easy discrimination task in the second study, in which active attention is more sustained by the number of repetitive selective attention tasks required. In aggregate, these effects, however, are few and subtle. Further studies are needed to clarify the nature and the conditions in which such effects can be seen, considering for instance ultradian rhythmicity, arousal level, task-related characteristics, and individual sensitivity.

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