Time-course of electromagnetic field effects on human performance and tympanic temperature

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The study aimed to investigate the time-course of electromagnetic field (EMF)-induced effects on human cognitive and behavioral performance and on tympanic temperature. Subjects were randomly assigned to two groups, exposed to a 902.40 MHz EMF before the testing session, or to the same signal during the data collecting session. Following a double-blind paradigm, subjects were tested on four performance tasks: an acoustic simple-reaction time task, a visual search task, an arithmetic descending subtraction task and an acoustic choice-reaction time task. Moreover, tympanic temperature was collected five times during each session. Results indicated an improvement of both simple- and choice-reaction times and an increase of local temperature on the exposed region under the active exposure. There was a clear time-course of the reaction time and temperature data, indicating that performance and physiological measures need a minimum of 25 min of EMF exposure to show appreciable changes. *NeuroReport* 15:161–164 © 2004 Lippincott Williams & Wilkins.

Key words: Cellular phones; Cognition; Electromagnetic field; GSM; Performance; Temperature; Time course

INTRODUCTION

The growing use of digital mobile telephones, using protocols such as the Global System for Mobile Communication (GSM), has recently raised hypotheses about the possible health effects of the radio-frequency electromagnetic field emitted by these kinds of phones [1]. At the same time, the close proximity of cellular phones to the human brain has stimulated discussions about the possible physiological interaction between these electromagnetic fields (EMFs) and human cerebral activity and behaviour [2,3]. Several studies have been conducted, taking into account the EEG spectral power of waking [4,5] and sleep [6,7], event-related potentials [8,9], reaction times [10,11], memory and cognitive performances [12,13], and subjective assessments [14]. Taken together, these studies have highlighted the following as a consequence of EMF exposure: variations of brain electrical activity (particularly in the alpha range; e.g. [5]), an improvement of performance (particularly when attention is required; e.g. [10,13]) and a total inability for human subjects to perceive the presence of EMFs (e.g. [14]). On the other hand, more recently, a multicentre study [15] failed to replicate and extend performance results.

In order to clarify the possible action mechanisms, other studies have turned their interest to the possible thermal variations induced by EMF exposure on the human head. Both experimental [16] and computational [17] approaches have highlighted an increase of local temperature subsequent to field exposure, and core temperature is positively related to human performance [18].

Nevertheless, some problems have still to be clarified regarding the features of bio-electromagnetic interactions. One of the open questions concerns when EMFs actually act. Some studies have looked into the effects after exposure [6], while others have examined the effects during exposure [10]. This could raise the question: if effects really do persist after exposure cessation, what are the temporal dynamics of the interactions between the GSM signal and human brain functioning?

Thus, the aim of the present study was to test, for the first time, the existence of a time-course of the effects of EMFs on psychomotor (reaction times) and cognitive performance (visual search and arithmetic subtraction), and on the tympanic temperature of human subjects.

MATERIALS AND METHODS

Twenty healthy subjects (10 men and 10 women) took part in the study and gave their written informed consent. Their mean (± s.d.) age was 26.4 ± 2.86 years (range 22–31). All were right-handed and regular mobile phone users, but none used their phone in the 10 h prior to the recording sessions (occurring at 10.00 h). A questionnaire and a clinical interview were used to exclude any neurological or psychiatric history, medication or drug intake and sleep complaints. The whole investigation was approved by the local Institutional Review Board and was conducted according to the principles established in the Declaration of Helsinki.

The mobile phone used was a Motorola Timeport 260, set by a test card to transmit a typical GSM RF-ON signal with a carrier frequency of 902.40 MHz at its maximum power of 2 W (equivalent to an average power of 0.25 W). It was held by means of a helmet in the classical use position (antenna oriented to the temporo-parietal areas and microphone oriented towards the mouth) at a distance of 1.5 cm from the left ear. A second phone was positioned on the right side of the head in order to balance the weight: this phone was never switched on. The exposure to the EMF was previously measured using a head phantom filled of semiliquid muscle equivalent material. As in the standards of compliance [19], the specific absorption rate (SAR) was evaluated inside the phantom by positioning a miniature field probe 1 cm in depth, over a grid of a few millimetres at the minimal distance from the shell containing the material, under the ear region. The phone was positioned in correspondence to the ear at a distance of 1.5 cm and switched on at its maximum power. In this experimental condition, a maximum value of SAR equal to 0.5 W/kg was measured.

Subjects were randomly assigned to one of two experimental groups: the first group (10 subjects, five females) was exposed to the GSM signal for 45 min before the testing session, while the second (10 subjects, five females) was exposed for the same amount of time, during the session itself. Thus, every session lasted 90 min a 45 min pre-recording period, followed by 45 min of data recording. Every subject was submitted to three sessions, in counter-balanced order: a baseline (BSL), a real exposure (EMF-ON) and a sham exposure session (EMF-OFF), with ≥ 48 h between tests, following a double-blind paradigm. During the BSL session, subjects wore only the helmet whereas during the EMF-ON and EMF-OFF sessions they wore both helmet and mobile phone. The BSL was recorded to obtain a normal level of performance avoiding any possible uncontrolled effect due to the presence of the mobile. Two days before the start of the experimental sessions, all subjects were submitted to training sessions in order to reach a stable performance level.

Each experimental session consisted of four tasks, always administered in the following order: an acoustic simple-reaction time task, a visual search task, an arithmetic descending subtraction task and an acoustic choice-reaction time task. Moreover, tympanic temperature was collected five times during each session: at the 1, 22, 45, 67 and 90 min. During the acoustic simple-reaction time task, the subjects were asked to press a button as rapidly as possible when they heard a tone (frequency 1000 Hz, intensity 75 dB) coming from a loudspeaker positioned in front of them, at a distance of 70 cm. The reaction times were recorded from both hands: since no significant difference was observed between the right and left hand, the mean values were considered. During the acoustic choice-reaction time task, subjects heard two different tones: the target and the standard stimuli, respectively of 1500 Hz and 1000 Hz. They were asked to respond to both kinds of stimuli by pressing the same button and to count mentally only the target ones: the target stimuli were 20% of the total tones. Subjects were instructed to report the total number of counted target stimuli to the experimenter at the end of the trial. The response was bimanual: since no significant difference was observed between the right and left hand, the mean values were considered for the subsequent data analysis. Both the simple- and choice-reaction time tasks lasted for 7 min and were administered with an inter-stimulus interval varying between 3 and 5 s.

The visual search task was a letter cancellation task in which subjects were asked to find and mark three target letters (reported on the top of the sheet) within a matrix of 1800 capital letters: 300 were target and 1500 non-target letters. The time allowed was 5 min.

During the arithmetic descending subtraction task the experimenter gave the subjects a three-digit number (such as 853): subjects were required to mentally subtract the number 9 from 853 and to say the answer aloud (844). The number subtracted progressively decreased by 1 until, after having reached the value of 2, it returned to 9. Subjects knew this rule and proceeded accordingly, without any intervention of the experimenter. Performance was audio-recorded and the allowed completion time was 3 min.

As dependent variables we considered both measures of speed and accuracy. For simple reaction times the median of responses was considered, while for the choice reaction times both median of responses and detection error rate were evaluated. The mean proportion of correct responses and the mean number of explored rows were taken into account for the visual search task. The mean proportion of correct subtractions and the total number of operations were quantified in the descending subtraction task.

A mixed design ANOVA group (before; during) $\times$ condition (BSL; EMF-ON; EMF-OFF) was applied to reaction times and also to performance speed and accuracy measures, while temperature evaluations were submitted to a mixed ANOVA group (before; during) $\times$ condition (BSL; EMF-ON; EMF-OFF) $\times$ time (1; 2; ... 5) $\times$ Side (left; right).

RESULTS

As evidence of the effectiveness of previous training, no statistical difference was observed between the baseline performance of the two groups.

No significant effect was observed for both speed and accuracy measures on the visual search task and descending subtraction task (Table 1).

Significant main effects for condition ($F(2,36) = 6.437$, $p = 0.004$) and group ($F(1,18) = 5.995$, $p = 0.02$) were found for simple-reaction times, indicating a speeding up of psychomotor responses under GSM exposure (Table 1) and a faster performance of the group exposed before the recording session (median = 248.97) with respect to the group exposed during the testing (median = 334.53). *Post hoc* comparisons (Scheffé's test) showed that the condition EMF-ON was significantly different from both BSL ($p < 0.02$) and EMF-OFF condition ($p < 0.005$). A similar main effect for condition was observed on the target stimuli ($F(2,30) = 5.797$; $p = 0.007$, Table 1) of choice-reaction times, again indicating a decrease in reaction times under the real exposure condition (EMF-ON). Also in this case, *post hoc* comparisons showed that the condition EMF-ON was significantly different from both BSL ($p < 0.02$) and EMF-OFF condition ($p < 0.002$). The main effect for group approached significance for target stimuli ($F(1,15) = 4.127$, $p = 0.06$), again pointing to reduced reaction times for the subjects exposed before. No differences were found in the error rate of target detection: only two of 20 subjects reported an incorrect number of targets.

Table I. ANOVA results for the median of reaction times and mean (± s.e.) of speed and accuracy measures of letter cancellation task (LCT) and descending subtraction task (DST), under different conditions.

	BSL	EMF-ON	EMF-OFF	F	df	*p*
Simple reaction times	297.6	265.56	312.08	6.437	2, 36	0.004
Choice reaction times	335.67	306.83	347.27	5.797	2, 30	0.007
LCT speed	19.58 ± 1.04	19.20 ± 0.88	19.80 ± 0.92	0.689	2, 34	n.s.
LCT accuracy	0.919 ± 0.01	0.925 ± 0.01	0.930 ± 0.01	1.206	2, 34	n.s.
DST speed	50.216 ± 4.09	47.8 ± 4.07	49.216 ± 4.64	0.753	2, 36	n.s.
DST accuracy	0.889 ± 0.02	0.887 ± 0.02	0.908 ± 0.02	1.405	2, 36	n.s.

Reaction time data are reported in milliseconds; speed measures are indicated as the number of explored rows (LCT) and the number of subtractions (DST); accuracy measures are reported as the proportion of correct responses (LCT) and the proportion of correct subtractions (DST).

With respect to tympanic temperature, a significant main effect was observed for side ($F(1,15) = 10.492$; $p = 0.005$), indicating a mild increase in the temperature of the exposed ear (+0.15°C) with respect to the non-exposed ear. A significant condition × ear interaction ($F(2,30) = 3.452$, $p = 0.04$) showed that the higher temperature over the exposed ear was evident only under the EMF-ON condition. Finally, a significant condition × time interaction ($F(8,120) = 3.184$; $p = 0.002$) indicated that the temperature in the EMF-ON session increased as a function of time, with the peak starting after ≥ 25–30 min of exposure.

Since parallel changes were found for temperature and reaction times under real exposure, the association between these measures was also assessed by product-moment correlations. Thus, the temperature variation (ΔT) between the start and stop of EMF-ON was correlated to the performance changes between EMF-ON and EMF-OFF session (% improvement = EMF-ON/EMF-OFF) for each group and for each dependent variable considered. No significant correlations were found between the speeding up of reaction times (improved performance) and the increase in tympanic temperature.

DISCUSSION

The present results suggest that the EMF emitted by a mobile phone may affect both human performance and tympanic temperature and that these effects have a specific time-course. Subjects exposed to a GSM signal showed a speeding up of reaction times with respect to the condition of baseline or sham field exposure. These results confirm others [10–13] showing a facilitatory effect on performance speed. In addition, subjects exposed for 45 min before testing performed better (i.e. they had faster reaction times) than subjects exposed during the task itself, and the effects of electromagnetic fields on brain functioning showed a specific time-course, with a faster psychomotor performance at the end of 45 min exposure than during sham exposure. This time course is consistent with changes in sleep EEG measures, that showed a peak of activity at 10.00–11.00 Hz and 13.50–14.00 Hz frequencies immediately after the EMF switch-off [20]. The small increase in tympanic temperature observed over the exposed ear in the EMF-ON condition was also time-dependent, starting after about 25–30 min exposure, as the computational data indicated [21]. No effects were found on error rate or other measures of accuracy, confirming most previous studies [10–12] which indicated that the influence of the electromagnetic field on the brain is restricted to speed processing. Finally, in contrast to some previous findings [10–12], cognitive and attentional tasks failed to show any influence of the presence of the field, on both speed and accuracy parameters.

The parallel changes of temperature and behavioural performance are suggestive of a causal link between the two phenomena, as previously proposed by some authors [10,11]. If we hypothesize that EMFs act by means of a thermal-like mechanism, we could expect a short-lasting effect mainly on speed measures, probably induced by an increase in brain metabolism or in chemical reactions at the synaptic level. In fact, a slight decrease of reaction times and a general increase in attentional and memory performance has been reported under exposure to EMFs [10–13], and changes in local cerebral blood flow, as assessed by PET, are induced 10 min after the end of exposure to electromagnetic fields [7]. This relatively short interval may suggest temperature-dependent mechanisms acting on synaptic transmission [11].

On the other hand, other mechanisms could alternatively be hypothesized. For example, the effects on sleep EEG measures were long-lasting, since a 30 min pre-sleep exposure induced an increase of sigma EEG activity across the night lasting up to 7 h after lights-off [7]. This finding was interpreted in terms of changes in cortical–subcortical loops as a consequence of exposure to electromagnetic fields. In our opinion, changes in brain temperature induced by EMF exposure, estimated to be nearly 0.1°C [17] and empirically evaluated in the present study at the tympanic level (0.15°C), could hardly have caused these strong and long-lasting effects: larger temperature increases are needed to obtain faster neural transmission [22].

Taking into account the intrinsic limitations of a correlational approach (on a relatively small group of subjects), the lack of significant correlations between the increase in local temperature and the facilitation of behavioural processing suggest that these effects are probably independent epiphenomena of EMF exposure. If this is true, cellular mechanisms, such as the modulation of membrane ionic channels [23] or the implication of heat shock proteins [24], should be taken into consideration. The consequent altered cell functioning may in turn modulate the physiological brain oscillations and consequently influence behaviour [1].

With respect to time-course effects, computational data have shown that a certain time is required to observe effects on brain and ear temperature, due to the great vascularization of the head [17,21]. Our data empirically confirm that an exposure of ≥ 25–30 min is needed in order to observe any appreciable increase in tympanic temperature, although no conclusion can be drawn about the duration of the effect. Thus, we can conclude that the increase in local temperature is just one of the several effects subsequent to EMF exposure, and that this epiphenomenon presents a specific temporal dynamic. Additional research is needed to further examine the time-course of the interactions between biological systems and electromagnetic fields, particularly with respect to the issue of the so-called wash-out time [25]. Although previous studies have shown that EMF-induced influences do exist on physiological and behavioural measures, at the present time it is not completely clear how long these influences last and whether the degree of persistency changes when considering different dependent variables [25].

CONCLUSION

Our results point to a specific time-course in the effects of electromagnetic fields on both brain functioning and tympanic temperature, with an interval of $\geq$ 25–30 min to observe physiological and behavioural changes. However, in the light of these data, it is not possible to draw any conclusions on the underlying physiological action mechanisms or on the possible health consequences of chronic exposure to EMFs.

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