

The effects of electromagnetic field emitted by GSM phones on working memory

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The influence of pulsed radiofrequency (RF) electromagnetic fields of digital GSM mobile phones on working memory in healthy subjects were studied. Memory load was varied from 0 to 3 items in an n-back task. Each subject was tested twice within a single session, with and without the RF exposure (902 MHz, 217 Hz). The RF field speeded up response times

when the memory load was three items but no effects of RF were observed with lower loads. The results suggest that RF fields have a measurable effect on human cognitive performance and encourage further studies on the interactions of RF fields with brain function. *NeuroReport* 11:1641–1643 © 2000 Lippincott Williams & Wilkins.

Key words: Cellular phones; Cognition; Electromagnetic field; GSM; Mobile phones; Working memory

INTRODUCTION

The introduction of digital mobile phones, especially GSM phones (Global System for Mobile Communication), has recently stimulated discussion about the possible health effects of the radiofrequency (RF) electromagnetic field emitted by these phones. As cellular phones are held very close to the head during their usage, and part of the radiated energy will be absorbed into the user's head, it is important to study the possible effects of RF fields on brain and behavior.

Studies on the impact of digital 900 MHz RF fields on the spontaneous EEG do not show any consistent effects [1,2] (but see [3]). However, studies on event-related brain activity suggest that the RF fields may influence brain activity when particular tasks are performed. Freude *et al.* [4] observed that RF field had an effect on preparatory slow brain potentials in visual monitoring but no effect was observed in a less demanding self-paced finger movement task. Eulitz *et al.* [5] found that RF exposure modulated high-frequency brain responses to task-relevant auditory stimuli but not to irrelevant standard stimuli. Krause *et al.* [6] observed that RF field altered the event-related desynchronization/synchronization of EEG power in a memory task, particularly during retrieval from memory.

Do the possible effects of RF fields on brain function have any consequences at behavioral or cognitive level? Preece *et al.* [7] studied the effects of analogue and digital 915 MHz RF fields on performance in a series of cognitive tests. The results showed that the response times in a choice reaction time task were speeded up during analogue

RF exposure. Koivisto *et al.* [8] studied the effects of pulsed digital 902 MHz RF field on performance in a larger variety of reaction time tasks. They found that the RF exposure speeded up response times in simple reaction time and in a vigilance task, and the cognitive time needed to accomplish mental arithmetics was decreased. However, the exposure did not have any effects on choice reaction tasks measuring various stages of visual object or word recognition, suggesting that the effect was not located at motor or visual processing levels. It was concluded that the digital RF field has a facilitating effect on cognitive processing in tasks that require attention or cognitive manipulation in working memory.

The present study examined the possible effects of RF exposure by a standard GSM phone on performance in sequential letter memory tasks [9,10] in which working memory load was varied. The number of letters kept in working memory was varied from 0 to 3 items between tasks while encoding and response execution stages were kept constant. Depending on the task condition, the subjects were asked to respond to each letter according to whether it appeared 0, 1, 2 or 3 trials back (n-back task). Each n-back condition was performed twice by each subject: with and without the RF exposure in a counter-balanced order. Thus the experiment allowed us to observe whether the possible effects of RF fields on RTs are modified by the working memory load. On the basis of the earlier work [8] suggesting that RF exposure speeds up RTs, especially in tasks calling for attention or manipulation of information in working memory, one could predict that the RF exposure would decrease RTs when the

cognitive load is heavy whereas no effects would be observed with lower levels of load.

MATERIALS AND METHODS

Forty-eight right-handed volunteers (24 male, 24 female) gave their informed written consent and participated in the experiment. Their mean age was 23.2 years (range 18–34). None had any neurological diseases. Three participants made more than 10% errors and they were replaced with new participants.

The stimuli were single letters (consonants) presented on a microcomputer screen in a pseudorandom order with varying lettercase. Stimulus presentation and data collection was controlled by a reaction time software [11] which synchronised the stimulus presentation with the raster beam. Four conditions were used: 0-back, 1-back, 2-back, and 3-back. In the 0-back condition, the target was the letter x. In the 1-back condition, the target was any letter that was presented one trial back (i.e., a sequence of the same letters in a different case such as f–F or B–b). In the 2-back condition, the target was any letter presented two trials back (e.g. R–c–r), and in the 3-back condition the target was any letter presented three trials back (e.g. h–T–k–H). Each letter was presented until the subject responded (or for 2 s at maximum), and the next stimulus was displayed after a 1 s interval. Subjects responded to the targets with their right index finger, and to the non-targets with their right middle finger. Both speed and accuracy was stressed in the instructions. Each condition included 36 targets and 84 non-targets, preceded by a practice block including 6 targets and 14 non-targets. In all conditions the target letters were never presented in the same lettercase as the same letter 1, 2 or 3 trials back. The order of the n-back conditions was counterbalanced across the subjects according to the balanced Latin square design.

Each subject received each n-back condition twice: once while the RF was on, and once while the RF was off. The order of the RF exposure was counterbalanced across subjects. Half of the subjects received the four n-back conditions first with simultaneous RF exposure and then without the exposure, whereas the other half received the RF exposure in the opposite order. The RF exposure lasted for about 30 min, which was the time that it took to

perform once all the four n-back conditions and their practice trials.

The RF exposure was given under single-blind conditions. A GSM phone was mounted on the subject's head during the whole test session. It was oriented in normal position for use with the earphone positioned on the left ear and the microphone orienting towards the corner of the mouth. The antenna was located about 4 cm apart from the head, over the posterior areas of the left temporal lobe. The phone was connected through a data cable to a laptop computer which was used to switch the RF on or off. The loudspeaker was removed so that acoustic cues could not indicate whether the RF was turned on or off. When the RF was on, the phone emitted 902 MHz electromagnetic field pulsed at a frequency of 217 Hz and with a pulse width of 577 μ s at 0.25 W mean power.

RESULTS

The RTs (see Table 1) in each condition were screened by removing items with latencies longer than 2 s.d. of each participant's mean. The RTs were analysed for correct responses only. In the ANOVAs including factors with more than two levels, the degrees of freedom were adjusted according to the Greenhouse–Geisser procedure, and only corrected degrees of freedom and significance levels are reported.

An ANOVA with RF (on *vs* off), load (0 *vs* 1 *vs* 2 *vs* 3-back) and type (targets *vs* non-targets) as within-subject factors and RF exposure order (2) as a between-subjects factor was performed on logarithmic transformations of the RTs. It revealed a significant main effect for load ($F(2,97) = 284.23$, $p < 0.001$), showing that as memory load increased, the RTs became longer. The main effects for RF or type were not statistically significant ($F < 1$). The RF $\times$ load interaction did not reach statistical significance ($F(2,109) = 2.25$, $p = 0.10$). Load interacted with type ($F(2,114) = 31.88$, $p < 0.001$), and more importantly, this interaction was modified by a significant RF $\times$ load $\times$ type interaction ($F(2,112) = 5.76$, $p < 0.01$). Inspection of Table 1 suggests that RF had a different effect on RTs to targets *vs* non-targets as memory load increased. The data were further analysed by conducting separate ANOVAs on targets and non-targets.

Table 1. Mean (s.d.) response times (RTs; ms) and error percentages to targets and non-targets in the different n-back conditions when the radiofrequency electromagnetic field was off (RF-off) or on (RF-on).

	RF off		RF on	
	RT	Errors	RT	Errors
Targets				
0-back	442 (61)	4.2 (4.8)	439 (59)	4.2 (4.8)
1-back	470 (90)	4.5 (3.9)	481 (90)	5.6 (4.8)
2-back	559 (120)	12.9 (10.1)	580 (146)	11.9 (9.1)
3-back	790 (181)	34.7 (13.9)	754 (192)	34.3 (12.4)
Non-targets				
0-back	396 (52)	1.2 (1.9)	401 (50)	0.4 (0.8)
1-back	471 (91)	1.7 (2.3)	480 (106)	1.4 (2.2)
2-back	631 (171)	4.3 (5.2)	632 (177)	4.9 (6.9)
3-back	764 (180)	15.2 (11.9)	769 (205)	15.2 (16.0)

The ANOVA for targets revealed a significant main effect for load ($F(2,99) = 248.24$, $p < 0.001$) and most importantly, a significant RF $\times$ load interaction ($F(2,108) = 5.13$, $p < 0.01$). This interaction shows that the effect of the RF exposure on RTs was dependent on the level of cognitive load. The RF exposure did not have any reliable effects in the 0-back condition ($F < 1$), 1-back condition ($F(1,46) = 3.36$), or 2-back condition ($F(1,46) = 2.14$). However, in the 3-back condition, the RF exposure speeded up RTs with 36 ms ($F(1,46) = 4.41$, $p < 0.05$).

The ANOVA for non-targets revealed a significant main effect for load ($F(2,102) = 235.84$, $p < 0.001$). The main effect for RF or the RF $\times$ load interaction was not statistically significant ($F < 1$). Thus, the RF exposure had an effect on targets only.

The error scores (see Table 1) were analysed by an ANOVA with RF (on *vs* off), load (0 *vs* 1 *vs* 2 *vs* 3) and type (targets *vs* non-targets) as within-subject factors and RF exposure order (2) as a between-subjects factor. It found significant main effects for load ($F(2,79) = 256.74$, $p < 0.001$) and type ($F(1,46) = 93.98$, $p < 0.001$), showing that increasing memory load induced more errors, and that less errors were made to non-targets than to targets. In addition, the load $\times$ type interaction ($F(2,70) = 33.15$, $p < 0.001$) showed that the difference in errors between targets and non-targets became larger as the load increased. Other effects involving load, type or RF were not statistically significant ($F < 1$), indicating that the RF exposure had no effects on accuracy. These results suggest that the effect of the RF exposure observed for RTs was not confounded by speed-accuracy trade-offs.

In sum, the results showed that the RF exposure speeded up RTs to targets when the memory load was highest (three items).

DISCUSSION

This study provides further support for the view that RF fields emitted by cellular phones have effects on cognitive and brain functions in humans [5–8]. The results from the n-back task showed that RTs to target letters were speeded up when the RF exposure was on. However, this effect was restricted only to the particularly demanding condition in which three items had to be kept in memory, whereas there were no RF effects in the conditions with memory loads of two items or less. The RF exposure had no effects on the accuracy of performance, suggesting that the RT facilitation in the 3-back condition was not gained at the expense of making rapid but erroneous responses. Importantly, the finding of no differences in the error patterns as well as in the RT patterns to non-targets between the exposure and nonexposure conditions suggests that the memory strategies used by the subjects were not changed between these conditions. This makes it unlikely that the subjects were conscious about the presence or absence of the RF field and thus they could not adjust their perform-

ance according to their own hypotheses concerning the possible effects of RF fields. On the other hand, the fact that the accuracy level did not increase during the RF exposure indicates that the gain obtained from the field was a small one and probably has no practical implications for performance in daily life.

The present pattern of results supports the view that the RF fields emitted by GSM phones affect higher level cognitive functions requiring a certain level of attention in contrast to simple motor execution or visual processing stages [8]. Brain imaging studies suggest that attention and working memory generally engage frontal and parietal cortices [12]. Interestingly, in the n-back task, memory load and brain activity exhibit a systematic relationship in these same frontal and parietal areas [9,10]. Further experiments using brain imaging methods (e.g. PET) could show whether the RF fields indeed have their influences on brain function in these areas. Such studies might also shed some light on the mechanisms of the RF influences on brain function. It has been suggested that the facilitation of cognitive processing during RF exposure might be generated by a slight temperature rise in brain tissue [7]. Possible temperature changes could be reflected in PET scans as changes in local cerebral blood flow.

CONCLUSION

In line with earlier electrophysiological and behavioral studies [4–8], the present study suggests that RF fields may have measurable influences on human brain function and cognition. With respect to the behavioral consequences of the RF fields in humans, all the available evidence point to the same direction: RF fields facilitate rather than disrupt performance. The physiological mechanisms underlying such influences are poorly understood, and it is too early to conclude what the significance of the observed effect is on human health.

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