

Mobile Phone Exposure and Spatial Memory

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Radiofrequency (RF) emission during mobile phone use has been suggested to impair cognitive functions, that is, working memory. This study investigated the effects of a 2½ h RF exposure (884 MHz) on spatial memory and learning, using a double-blind repeated measures design. The exposure was designed to mimic that experienced during a real-life mobile phone conversation. The design maximized the exposure to the left hemisphere. The average exposure was peak spatial specific absorption rate (psSAR10g) of 1.4 W/kg. The primary outcome measure was a “virtual” spatial navigation task modeled after the commonly used and validated Morris Water Maze. The distance traveled on each trial and the amount of improvement across trials (i.e., learning) were used as dependent variables. The participants were daily mobile phone users, with and without symptoms attributed to regular mobile phone use. Results revealed a main effect of RF exposure and a significant RF exposure by group effect on distance traveled during the trials. The symptomatic group improved their performance during RF exposure while there was no such effect in the non-symptomatic group. Until this new finding is further investigated, we can only speculate about the cause. Bioelectromagnetics 30:59–65, 2009. © 2008 Wiley-Liss, Inc.

Key words: provocation study; radiofrequency fields; memory; virtual morris water task

INTRODUCTION

Daily, millions of people use mobile phones, and there is a growing concern among the general public that radiofrequency (RF) emissions from mobile phones impair health and cognitive functions. In a 2006 survey, European citizens were asked if they believed electromagnetic fields in the environment could potentially damage their health [European Commission, special Eurobarometer 272a]. Of 30000 participants, 28% believed that mobile phone handset strongly harmed their health, and only 22% did not believe it had any impact on health. Furthermore, a Swedish population survey reported that a third of the participants had concerns of possible health risks due to mobile phone use [Orpana, 2004]. Despite much research, there is a lack of consistent findings as to the possible cognitive effects from mobile phones. Most studies in humans have not demonstrated any significant effects from Global Systems of Mobile Communications (GSM) RF on either reaction time, short-term

memory, attention, information processing speed, memory and executive function, nor spatial memory in adults [Haarala et al., 2004, 2007; Besset et al., 2005; Russo et al., 2006; Wilen et al., 2006]. The few studies on children have not shown any effects on cognitive function in children [Preece et al., 2005]. However, in a recent study in adults a decrease in reaction time and

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increased accuracy in a working memory test following 30 min exposure to pulse modulated or continuous wave of 900 MHz radiofrequency fields was reported [Regel et al., 2007]. Increased responsiveness in choice reaction time during analogue simulation has been reported and GSM-like exposure at 915 MHz showed a trend of increased responsiveness [Preece et al., 1999]. Resting EEG and phase-locked neural responses to auditory stimuli were measured while a mobile phone was either operating or turned off. It was suggested based on the results that active mobile phones affect neural function in humans and do so as a function of exposure duration [Croft et al., 2002].

The inconsistencies reported in the literature of human studies of GSM-like RF exposure and cognitive functions are likely to be partially attributable to variations in study design, that is, in exposure frequencies, duration of exposure and exposure localization as well as controlling for increased heat sensation which occurs during real RF exposure [Karger, 2005; Kuster et al., 2007; Boutry et al., 2008]. The selection of the study population, for example, identifying subjects with prior problems attributed to mobile phone use, cognitive tests and cognitive domains are also of critical importance [Preece et al., 1999; Krause et al., 2004].

The present double-blind study was designed to control for many concerns that have been raised in studies of mobile phones and cognitive function. We used an exposure set-up and duration reflective of worst-case scenario. The applied exposure simulated the maximum human exposure during a 3 h GSM phone conversation at a carrier frequency of 884 MHz resulting in time averaged peak spatial specific absorption rate (psSAR10g) of 1.4 W/kg. Heat sensation, which might give away the true exposure condition, was controlled by externally applied heat, regardless of the actual exposure condition. In addition, we included a study group that reported having experienced symptoms of headache, vertigo or other kinds of pain or discomfort in the head in relation to mobile phone exposure. We also used a thoroughly validated and more complex test of cognitive functioning; the virtual Morris Water Task [vMWT], which is designed to replicate the procedures of the Morris Water Maze [Morris et al., 1982] a test which has been used extensively in RF exposure studies in non-human species [Lai et al., 1998; Wang and Lai, 2000].

OBJECTIVES

The purpose of this study was to investigate the effects on spatial memory performance of exposure to RF fields typical of that emitted from GSM mobile

phones in subjects *with* and *without* self-reported symptoms attributed to mobile phone use.

MATERIALS AND METHODS

Study design. The study design was a double-blind cross-over provocation study, comparing possible effects during exposure to RF and sham exposure. Subjects were defined as “symptomatic” (SG) if they reported having experienced one or more of the following specific symptoms: headache, dizziness or other kind of pain or discomfort in the head in relation to the use of mobile phones. A subject just reporting a sensation of heat during mobile phone calls did not qualify as “symptomatic.” The “non-symptomatic” group (NG) reported no such symptoms. A total of three sessions were conducted; a habituation session to get used to the laboratory set-up preceded the two exposure sessions. During the habituation session neither RF nor Sham was conducted. The study had a balanced block design, that is, approximately half of the subjects started with true RF exposure, the other half with sham. The Ethics Committees for Research at the University of Uppsala (Dnr: 2004: M-146) and Wayne State University (WSU HIC 013006P2X) approved the study.

Participants. The participants were between 18 and 45 years of age (mean age 29 ± 7). Exclusion criteria were attribution of symptoms to electrical equipment other than mobile phones, current medical or psychological illnesses, a history of brain injury, ongoing medication, sleep disorders, hypertension and pregnancy. Demographics and daily call time information of the study group ($N = 42$) are reported in Table 1.

Exposure. The exposure conditions simulated the maximum human exposure during a GSM phone conversation at a carrier frequency of 884 MHz, and

TABLE 1. Demographics and Baseline Assessments of the Study Group; Symptomatic Group Were Subjects who Reported Having Experienced Headache, Vertigo or Other Cerebral Symptom in Relation to Mobile Phone Use, the Non-Symptom Group did not Report any Experience of Symptoms in Relation to Mobile Phone Use

	Symptomatic group ($n = 23$)	Non-symptomatic group ($n = 19$)
Age (years)	28.8 ± 7	29.4 ± 6
Female	14	7
Male	9	12
Daily call time		
<20 min	13%	42.1%
20–40 min	26.1%	15.8%
>40 min	60.9%	36.8%
No information	0%	5.3%

compliant with the GSM standard. The exposure during non-Discontinuous Transmission mode (non-DTX) was set to a psSAR_{10g} of 1.95 W/kg and during DTX to 0.23 W/kg. The temporal change of non-DTX and Discontinuous Transmission modes (DTX) was random with an average duration of 11 s for non-DTX and 5 s for DTX resulting in a time-averaged psSAR_{10g} of 1.4 W/kg. For more quantitative descriptions of the SAR determination, see Table 2. Hence, the exposure was well below the ICNIRP guidelines of 2 W/kg [ICNIRP, 1998]. The exposure was applied by a patch antenna on the left side of the head, simultaneously exposing all possible exposure footprints of mobile phones [Kuster et al., 2004], see Figure 1. Spatial memory performance was assessed after 2.5 h exposure at 10 p.m. The exposure was designed to maximize the exposure of that brain tissue in the left hemisphere that is exposed during actual usage of GSM phones. For more detailed information see Hillert et al. [2008].

Virtual Morris Water Task

For behavioral navigation testing, subjects completed a Virtual Morris Water Task [vMWT], modeled after the Morris Water Maze and further developed and validated previously [Moffat and Resnick, 2002]. Hidden beneath the surface of the arena was a platform, and the task required the participant to locate the platform as quickly as possible. Because the platform was not visible to the participant, it had to be located with reference to its position relative to external objects and cues. When the participant passed over the platform, the platform became visible and raised the participant above the water level. The participant remained on the platform for 12 s during which time they could look around the arena but could not leave the platform. Following the 12 s delay, participants were automatically “transported” to a new location in the pool and facing a random orientation. A total of seven consecutive trials was conducted during each vMWT test. Two vMWT tests were conducted during each session, the two test episodes are denoted: “time:” early = before exposure and late after 2 h 30 min of exposure. Movement was controlled with a joystick (Logitech, model Attack



Fig. 1. The exposure situation, a headset with a fixed antenna placed on the left side of the head and a ceramic plate attached to the left ear lobe for heating.

3198, Stockholm, Sweden) and the environment was presented on a 15 inch computer monitor (NEC AccuSync LCD51vm, Stockholm, Sweden).

Statistical Analysis

Distance. The primary dependent variable used in the analysis was the distance traveled on each trial of the vMWT, in which shorter distances demonstrate better performance.

Repeated measures ANOVAs were used for statistical analysis. Variables in the models included group (SG vs. NG) as a between subjects factor and exposure (RF vs. Sham), session (1 vs. 2), time (early vs. late) and trial (1 to 7) as repeated measures. Statistical significance was set at a two-sided *P*-value of less than 0.05. Huynh-Feldt corrections were used to correct for unequal variances.

Outlying data, >2.5 standard deviations (SD) from mean, were substituted with the total sample mean for each variable, and missing raw data for trial were substituted with the population mean for the specific trial. However, if more than 2 trials were missing on any test (trial 1–7), no substitution was made and data were considered missing. Using above criteria, 3.6% of data were substituted.

TABLE 2. Exposure Values Induced in the Brain at Exposure Settings of 1.4 W/kg

	avgSAR ^a , W/kg (SD)	psSAR _{1g} ^b , W/kg	Inter-subject variations psSAR _{1g} (%)	Uncertainty psSAR _{1g} (%)
Grey matter	0.20 (0.26)	1.78	7	6
White matter	0.18 (0.21)	1.12	7	4
Thalamus	0.18 (0.06)	0.30	14	10

^a10 g averaged peak spatial SAR.

^b1 g averaged peak spatial SAR.

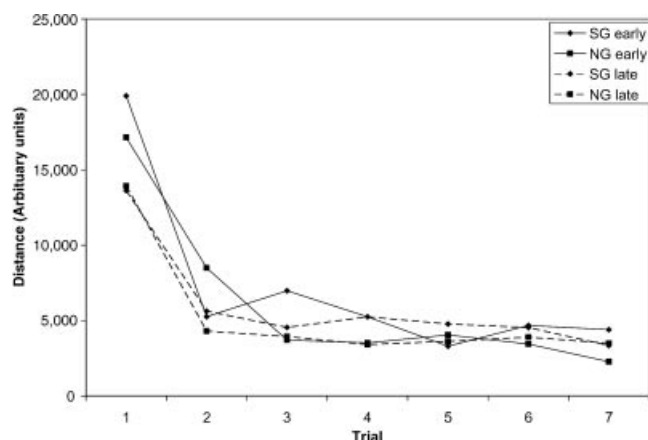


Fig. 2. The distance traveled in spatial memory test at early and late testing time in the symptomatic and non-symptomatic groups during habituation sessions. No statistically significant differences were found, either between the exposure conditions or between the groups.

RESULTS

A repeated measures ANOVA was performed with distance on each trial as dependent variable. There was a highly significant trial effect ($F = 39.72$; $df = 1228$; $P < 0.001$); that is, distance traveled decreased with consecutive trials (see Fig. 2 and Table 3). This was true during both the early testing time, before exposure started and late testing time, after 2 h and 30 min of exposure, thus indicating that there was no memory carry over effect from the early to the late test. No pre-existing performance differences (during habituation) were found between the groups on the vMWT, that is, improvement during the seven consecutive trials. The interaction between early and late testing time $\times$ trial showed a significant effect ($F = 2.84$; $P < 0.05$). During the exposure sessions (sham or RF) there were no statistically significant differences, either between the exposure conditions or between the groups at the early testing time, 6 p.m., before exposure started. During the late testing time a significant RF effect of exposure ($F = 5.35$; $df = 1,38$; $P < 0.026$) was found in which

distance traveled decreased during RF exposure compared to sham. In addition, there was a significant exposure by group effect ($F = 5.44$; $df = 1, 38$; $P < 0.025$), in which the symptomatic group improved their performance during RF exposure compared to sham; see Figure 3 and Table 4. No significant RF exposure by trial effect was found. There was no significant effect of session (first or second) on the results in the late test.

DISCUSSION

This study demonstrated a statically significant association between RF exposure and spatial memory performance. The effect indicates the differences in performance during RF and Sham to be general throughout the test since no significant interaction of trial was obtained. The effects appeared to be more accentuated in the SG-group. The symptomatic group improved their performance (shorter distance traveled), but only to a level comparable to that of the non-symptomatic group.

Spatial navigation is an important and complex cognitive skill that is often taxed in conjunction with mobile phone use, while driving, for example, and thus may be particularly suitable for investigation in a study of possible effects of RF exposure in the mobile phone frequency band. Age and gender differences have earlier been reported to impact the spatial memory function. Younger subjects perform better than older ones. Furthermore, it is suggested that males outperform females in spatial memory tasks, except on object-location memory tasks [Iachini et al., 2005; De Goude and Postma, 2008]. In the present study there were no age differences between the symptomatic and non-symptomatic groups; however, the symptomatic group consisted of more women. This gender effect might have an impact on the general performance level but not specifically explain the observed differences in connection to RF exposure. Until this new finding is further investigated, we can only speculate about the cause. One possibility is that the SG, being more

TABLE 3. Means (Standard Error; Units in Table Divided by 10^3) for Spatial Distance Traveled During Habituation Session for Symptomatic (SG) and Non-Symptomatic (NG) Groups at 18:00 (Early) and 22:00 (Late). The Distance is Measured in Virtual Units.

Trial	Early SG, means (SE)	Early NG, means (SE)	Late SG, means (SE)	Late NG, means (SE)
1	20.0 (2.7)	17.1 (3.0)	13.6 (1.9)	13.9 (2.2)
2	5.2 (1.2)	8.4 (1.3)	5.6 (0.8)	4.3 (1.0)
3	7.0 (1.2)	3.7 (1.4)	4.5 (0.6)	3.9 (0.7)
4	5.2 (0.8)	3.5 (0.9)	5.2 (0.8)	3.4 (1.0)
5	3.3 (0.8)	4.0 (0.9)	4.7 (0.8)	3.6 (0.9)
6	4.6 (0.6)	3.4 (0.7)	4.5 (0.8)	3.8 (0.9)
7	4.3 (0.7)	2.2 (0.8)	3.3 (0.4)	3.4 (0.5)

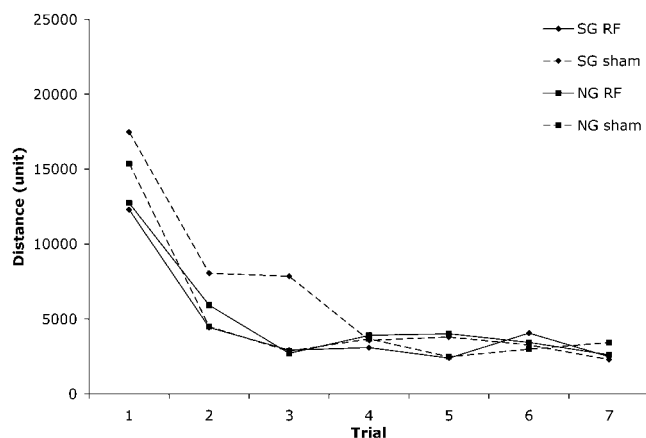


Fig. 3. The distance traveled at late spatial memory testing time (10.00 p.m.) during RF and sham exposure conditions for respective group. The difference between RF and sham exposure was significant ($P < 0.05$) and there was a significant exposure by group effect.

sensitive to environmental stimuli, has reacted to the environment in the test-lab, for example, the lower than everyday exposure to electromagnetic fields in the shielded environment or to a stressful situation of a possible symptom-triggering exposure, and that this reaction was cancelled out by the RF exposure. If, for example, the symptomatic group is more distracted or less concentrated during the late Sham exposure, this would be expected to be reflected especially during the first part of the late testing session when the learning is highly involved. It is possible that RF exposure contributes to a biological arousal improving attention in the symptomatic group and thereby contributing to the improved performance where the SG attained the same performance level as the NG group.

An important question arises regarding the possible neural mechanisms of our observed effects. Several previous studies suggest direct *neural* effects of GSM exposure including studies which have directly measured brain electrical potentials or cerebral blood flow measured by Positron Emission Tomography

[Bordely et al., 1999; Croft et al., 2002; Huber et al., 2002; Loughran et al., 2005; Aalto et al., 2006]. It is noteworthy that both studies [Huber et al., 2002; Aalto et al., 2006] observed increases in regional cerebral blood flow in the prefrontal cortex which was somewhat distal to the exposure site. The authors attributed these results to direct neuronal effects mediated by temporal-frontal and thalamus-cortical fiber tracts.

Spatial navigation is a complex cognitive function that depends on several neural and cognitive systems for successful completion. Functional neuro imaging and lesion studies have identified a network of structures that are involved in spatial navigation. The proposed network includes several cortical and sub-cortical structures with most attention being focused on the role of the hippocampus, parahippocampal gyrus, cerebellum, parietal cortex, posterior cingulate gyrus, pre-frontal cortex, retrosplenial cortex and other cortical and sub cortical regions [Aguirre et al., 1996; Barrash, 1998; Maguire et al., 1998]. However, navigation also requires higher-order cognitive processing such as the selection of an appropriate search strategy and appropriate behavioral monitoring and alterations of searching behavior if the selected strategy proves unsuccessful [Moffat et al., 2006]. Navigation also involves significant working memory demands because, within a trial, participants must remember preceding moves and locations and continually update this information to avoid immediately returning to the same (incorrect) locations [Moffat et al., 2007].

Given the findings of direct effects of RF exposure on brain physiology the present results may conceivably be attributable to direct effects of RF exposure on the neural or cognitive systems supporting human navigation.

SUMMARY

The current study provides some support for cognitive and possibly neural effects of GSM-like RF

TABLE 4. Means (Standard Error; Units in table Divided by 10^3) for Spatial Distance Traveled during Radio Frequency Exposure and Sham Exposure for Symptomatic (SG) and Non-Symptomatic (NG) Groups at 22:00. The Distance is Measured in Virtual Units.

Trial	RF SG means	RF SG SE	Sham SG means	Sham SG SE	RF NG means	RF NG SE	Sham NG means	Sham NG SE
1	12.3	(1.9)	17.5	(2.9)	12.7	(2.2)	15.4	(3.3)
2	4.4	(1.0)	8.1	(1.7)	6.1	(1.2)	4.5	(1.9)
3	2.9	(0.5)	7.9	(1.9)	2.7	(0.6)	2.8	(2.2)
4	3.1	(0.6)	3.6	(0.7)	4.0	(0.6)	3.7	(0.8)
5	2.2	(0.4)	3.8	(0.7)	4.0	(0.5)	2.5	(0.8)
6	4.1	(0.8)	3.3	(0.5)	3.4	(1.0)	3.0	(0.6)
7	2.5	(0.2)	2.3	(0.3)	2.6	(0.3)	3.4	(0.4)

emissions. Our results suggest some enhancing effects of GSM exposure on spatial memory and provide no support for the hypothesis that cognitive function may be adversely affected by acute mobile phone RF exposure. In addition, our results suggest the possibility that the effects of GSM-like RF exposure are subtle and may only be detected in subjects who report being sensitive to mobile phone use. The results need to be replicated using a larger battery of cognitive tests and in conjunction with brain imaging methods to determine the specificity and possible neural mechanisms of our findings. Moreover, further research is needed to elucidate possible psycho-physiological mechanisms contributing to these findings as well as possible mechanisms linking RF to cognitive effects.

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