Effects of mobile phone use on brain function, information processing and cognition: Phase I.

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Evidence suggests mobile phone radiation (EMF – Electromagnetic Fields) may have effects on cognition and brain function. The most consistent finding has been an increase in scalp-recorded electroencephalographic (EEG) alpha activity over parietal and occipital sites. Furthermore, a facilitating effect on cognition has been found, mainly on attention. It is still unclear, however, whether GSM radiation has any profound chronic effects on brain function and/or cognition, since all studies investigated acute exposure to EMF. The current study employs the recently developed International Brain Database to investigate the potential long term effects of mobile phone use on brain function and cognition.

Objectives: The primary objective of the present study is to evaluate whether any differences in brain function, information processing or cognition exist in people characterized as ‘heavy mobile phone users’ compared to non-users and intermediate mobile phone users.

Method: The present study makes use of data acquired from International Brain Database (six laboratories: two in USA, two in Europe, two in Australia). The data analyzed in this study include parameters based on spectral analyses of the electroencephalogram during eyes open and closed, amplitudes and latencies of evoked potentials obtained in an auditory oddball task, outcomes of personality (NEO-FFI) and neuropsychological tests (Digit span - forward and reverse -, Corsi Block Tapping test, Word Interference and Switching of Attention test (Part A and B)). Data from 300 healthy volunteers were used in the current study.

Results: The differences between the groups were generally small, however, there were significant differences between the groups. The heavy user group performed better on the Word Interference test as indicated by the Word Interference score, suggesting they have better focused attention. Furthermore, the heavy user group showed overall increased delta and theta activity and a decrease in alpha peak frequency localized in the right temporal region.

Conclusion: The interpretation of the results and conclusion will be further worked out in the forthcoming publication.

Introduction

Industry sources suggest that there will be over one billion mobile phone (GSM) users worldwide by 2005 (Repacholi, 2001). With the rapid and widespread increase in use worldwide, it is important to establish whether frequent mobile phone use has any adverse effects on health.

In order to communicate with base stations, mobile phones transmit electromagnetic fields (EMF) in the range of 900 MHz to 1800 MHz. EMF may have adverse effects on biological tissue such as the skin or the brain due to for example heat exchange. Several studies employing computational models have revealed that the radiation effect on the nearby skin is in the range of 0.25 degrees and on the brain is in the range of 0.12 degrees Celsius (van Leeuwen et al., 1999; Bernardi, et al., 2000; Wainwright, 2000; Wang & Fujiwara, 1999). Other-non-thermal mechanisms of the effect of EMF-biological tissue interaction have also been proposed (see Banik, Bandyopadhyay & Ganguly, 2003). However, to date none of these theories have received experimental support (Repacholi, 2001).

Several studies have explored the effects of electromagnetic fields (EMF) on brain function, especially in relation to electromagnetic radiation from cellular phones. For the effects of EMF on health (e.g. cancer) we refer to other reviews such as the Dutch Health Council advice (Dutch Health Council, 2002) or the IEGMP report (IEGMP, 2000).

Some animal studies have revealed that low frequency EMF might impair spatial learning in rats (60 Hz EMF: Lai et al., 1998; Lai, H. 1996) and mice (50 Hz Sienkiewicz, Haylock & Saunders, 1998). However, other studies employing high frequency EMFs - in the range of mobile phones (900-1800 MHz) - have revealed no effects on spatial learning (Dubreuil & Edeline, 2002; Dubreuil, Jay & Edeline, in press; Sienkiewicz et al., 2000). After extensively reviewing all available data from animal studies the IEGMP (IEGMP, 2002) concluded that findings from animal studies could mostly be attributed to high increases in body or brain temperature, resulting from high EMF exposure levels, not comparable to real-life GSM exposure levels.

Other studies have investigated the effects of EMF exposure on cognitive function/information processing in humans. Most studies have reported a facilitating effect of acute EMF exposure on cognition, e.g. faster reaction times (Preece, et al. 1993; Koivisto et al., 200)) or better performance in attention tasks without an increase in the number of errors made (Lee et al., 2001; 2003; Koivisto et al., in press). Other studies have employed brain activity (EEG) to assess the effects of acute EMF on brain function. The most consistent finding in healthy volunteers is an increase in alpha EEG activity, mainly in the parietal and occipital areas of the brain (Waking EEG: Croft et al., 2002; Schulze et al.; Mann & Röschke, 1996; Krause et al., 2000; Polysomnographic EEG: Lebedeva et al., 2001; Borbely et al., 1999; Huber et al., 2000; 2002 a; 2002 b). Furthermore, an increases in theta power (Lebedeva et al., 2001), modulation of high frequency induced brain activity (Eulitz et al. 1998) and a decrease in the correlation dimension (Lebedeva et al., 2001) have been reported. Others, however, found no effects of acute EMF exposure on spectral measures of the wake and sleep EEG (Röschke & Mann 1997; Wagner et al. 2000; Eulitz et al. 1998). Furthermore, Hladký et al. (1999) and Urban et al. (1998) found no effects of GSM exposure on visual evoked potentials.

All these studies have experimentally investigated the putative – acute – effects of EMF on brain function. Some of the above studies summarized have been criticized on statistical grounds or other methodological grounds (see also IEGMP, 2000), but even if all effects are genuine one can’t draw any conclusions concerning the long term – real life - effects of chronic EMF exposure. To the best of our knowledge, no naturalistic studies have been performed in which the long term effects of EMF radiation on brain function and information processing have been investigated. In the present study we seek to investigate the effects of long-term – real life – GSM usage on brain function and information processing.

Method

Subjects

The present study makes use of data acquired by The Brain Resource Company (the International Brain Database). Six laboratories (New York, Rhode Island, Nijmegen, London, Adelaide and Sydney) participated in the highly standardized data acquisition procedures using identical amplifiers and other hardware, paradigm details, software acquisition and task instructions. Five hundred and forty fifty apparently normal individuals (mean age, 33 years, age range 11-70 years, balanced for gender) were initially included. Exclusion criteria included a personal history of mental illness (or a family history of Attention Deficit Hyperactivity Disorder (ADHD), Schizophrenia, Bipolar Disorder, or genetic disorder), physical brain injury, neurological disorder or other serious medical condition, and/or a personal history of drug or alcohol addiction. All subjects (or their guardians for subjects less than 18 years of age) voluntarily signed a written informed consent. Subjects were additionally required to refrain from caffeine and smoking for at least 2 hours prior to testing.

Prior to data acquisition subjects answered 22 self-report questionnaires about personality, emotional experience, mobile phone use, general health and addictive behaviours.

Mobile phone use questionnaire

The questionnaire used to ascertain the extent of mobile phone use by individuals, consisted of the following questions with their respective answers and corresponding score between commas:

Q0: Do you use a mobile phone?
Yes / no
Q1. How often do you use a mobile phone (to make or receive a call)?
(4) Many Times a day / (3) A few times a day / (2) Once a day / (1) Once every few days / (0) Once a week or less.
Q2. What would be the duration, on average, of each call?
(1) Less than 5 minutes / (2) 5-10 minutes / (3) 10-15 minutes / (4) 15-20 minutes / (5) greater than 20 minutes.
Q3. How much time, on average, would you spend on the mobile phone each day?
(1) Less than 10 minutes / (2) 10-30 minutes / (3) 30-60 minutes / (4) 60-90 minutes / (5) greater than 90 minutes.
Q4. How many years have you been using a mobile phone?
(1) Less than 1 year / (2) 1-2 years / (3) 2-3 years / (4) 3-5 years / (5) Greater than 5 years.

The following two ranking variables were constructed from these data:

Recent Usage Intensity (RUI): Q1 X Q2 X Q3
Usage History (UH): Q4

Psychophysiological data acquisition

Participants were seated in a sound and light attenuated room, set at an ambient temperature of 22°C. EEG data were acquired from 32 channels: Fp1, Fp2, F7, F3, Fz, F4, F8, FC3, FCz, FC4, T3, C3, Cz, C4, T4, CP3, CPz, CP4, T5, P3, Pz, P4, T6, O1, Oz and O2 electrode sites, 4 EOG channels, orbicularis oculus and masseter (Quikcap; NuAmps; 10-20 electrode international system). Data were recorded relative to the virtual ground, but referenced offline to linked mastoids. Horizontal eye movements were recorded with electrodes placed 1.5cm lateral to the outer canthus of each eye. Vertical eye movements were recorded with electrodes placed 3mm above the middle of the left eyebrow and 1.5cm below the middle of the left bottom eye-lid. Skin resistance was < 5 kOhms for all electrodes. A continuous acquisition system was employed and EEG data were EOG corrected offline (Gratton et al., 1983). The sampling rate of all channels was 500 Hz. A low pass filter with attenuation of 40dB per decade above 100 Hz was employed prior to digitisation.

The EEG data were recorded during eyes open and eyes closed, and the ERP data were drawn from an auditory oddball paradigm, where the EEG eyes open, eyes closed preceded the auditory oddball paradigm.

During the eyes open paradigm, subjects were asked to sit quietly with their eyes open, looking at the red dot on the screen in front of them. This task lasted for two minutes. The eyes closed paradigm was almost identical, the only difference being that subjects were asked to rest quietly with their eyes closed for the two-minute duration.

During the auditory oddball paradigm subjects were presented with a series of high and low tones, at 75dB and lasting for 50ms, with an ISI of 1s. Rise and fall times of the tones was 5ms. Subjects were instructed to button press with the index finger of each hand in response to ‘target’ tones (presented at 1000Hz). They were asked not to respond to ‘background’ tones (presented at 500Hz). Speed and accuracy of response were equally stressed in the task instructions. The background and target tones were presented in a quasi-random order, with the only constraint being that two targets cannot appear consecutively. The duration of the auditory oddball task is approximately six minutes. Probability of the odd stimulus was 15%.

Statistical analysis

For the purpose of analyzing the variables of interest in the current study, data were limited to subjects older than 18 years of age who were right handed. The data of 445 subjects were used. Data from the mobile phone use questionnaire were used to make the three groups, by sorting the data on Recent Usage Intensity (RUI) and then on Usage History (UH). The Top-100 users on RUI were then marked as the 'Heavy user group'. The naïve user group consisted of 100 subjects who answered Q0 with 'no'; and the 'intermediate user group' were selected from the remaining subjects who answered Q0 with 'yes'. The three groups were randomly matched on gender, age, handedness, Clinic ID (location where they were tested) and education level.

All statistics were performed using SPSS 11.5.1 for Windows. Group characteristics were analyzed by a one-way ANOVA, in case of a significant group effect the comparisons between the three groups were made with Bonferroni post-hoc tests. Neuropsychological results were analyzed with a Multivariate General Linear Model (GLM) procedure with 'group' as a between subject (fixed) factor and Extraversion and Openness as covariates, in order to reduce the chance for false positives. Reported F-values and significance levels for Multivariate effects are based on Pillai's Trace and for post hoc tests on Bonferroni. If appropriate, the neuropsychological data were further assessed with univariate ANOVA's to assess more specific effects of mobile phone use on the outcomes of the various neuropsychological performance tests.

EEG data were submitted to a multivariate analysis with within subject factors Condition (Eyes Open / Eyes Closed), Electrode Location (Left Temporal, Central and Right Temporal) and EEG frequency (delta, theta, alpha and beta) and between subject factor Group (Naïve, Intermediate and Heavy user group). As covariates Extraversion and Openness were used. Reported within subject findings are based on Pillai's Trace. Depending on significant interactions this analysis was repeated by taking the interacting factor out of the analysis. Post Hoc test were performed using simple contrast for the between subject factor. alpha peak frequency was analyzed in the same way, where EEG frequency was replaced by alpha peak frequency.

ERP data were submitted to a multivariate analysis with within subject factors Electrode Location (Left Temporal, Central and Right Temporal) and Component (N1 amplitude, N1 latency, P2 amplitude, P2 latency, N2 amplitude, N2 latency, P3 amplitude and P3 latency) and between subject Group (Naïve, Intermediate and Heavy user group). As covariates Extraversion and Openness were used. Depending on significant interactions this analysis was repeated by taking the interacting factor out of the analysis. Post Hoc test were performed using a simple contrast for the between subject factor.

Personality
The personality inventory is based on the NEO–FFI (Five Factor Inventory) for Windows software by PARInc. It comprises 60 Questions with a 5 point scale based on Costa and McCrae's RR (1992) NEO-FFI. It delineates five personality traits: conscientiousness, agreeableness, neuroticism, extraversion and openness.

Neuropsychology
The following neuropsychological tests and measures were used in the analysis:
Corsi Block Tapping Test: number correctly reproduced; Digit Span: number correctly reproduced; Reverse Digit Span: number correctly reproduced; Word Interference: number correct word condition, Number correct color condition, Word Interference Score (Number Correct word condition – color condition); Switching of Attention test part A and B: number correct, number of errors.
The word interference test is similar to the Stroop test, in that subjects in the first part (word condition) are required to identify the word (presented in different colors); and in the second condition (Color) are required to identify the color of the words. The performance score is number correct in 1 minute.

The Switching of Attention test is similar to the Trail making test part A and B, in that subjects are required to connect numbers (1, 2, 3…: part A) and numbers and letters (1, A, 2, B…: part B).

EEG scores

Average power spectra were computed for eyes open and eyes closed paradigms. Two minutes of EEG were acquired for both eyes open and eyes closed condition. These two minutes of EEG were divided into adjacent intervals of four seconds. Power spectral analysis was performed on each four second interval by first applying a Welch window to the data, and then performing a Fast Fourier Transform (FFT). The resulting power spectra were averaged for the two conditions, yielding an eyes open and an eyes closed average power spectrum for each electrode position.

The power was calculated in the four frequency bands for both spectra, delta (1.5 - 3.5 Hz), theta (4 - 7.5 Hz), alpha (8 - 13 Hz), and beta (14.5 - 30 Hz). This power data were then square-root transformed in order to fulfill the normal distributional assumptions required for parametric statistical analysis.

In order to reduce the dataset, 3 functional areas were defined (locations are based on the 10-20 classification) and averaged EEG power of these sites were used. The functional areas were those who are closest to the ears, e.g. where the phone is usually held - and the central area - in order to observe overall effects on brain function. The areas chosen were T3 and T5 at the left temporal area; FCz, Cz, CPz and Pz as representing the central area; and T4 and T6 for the right temporal area.

Data from other locations were discarded for this study.

ERP scores

Average ERPs were calculated for target epochs. The individual single-trial epochs were filtered with a low-pass Tukey (cosine taper) filter function that attenuated frequencies above 25 Hz. The single-trials were then averaged to form conventional ERPs. The N1, P2, N2 and P3 ERP components were identified.

Results

The subject characteristics, means, SD's and p values of the three groups are presented in Table 1. There were no differences on group characteristics. There were differences between the groups for mobile phone use (RUI and HU), indicating that the groups only differed in mobile phone use and were adequately matched.

Table 1: Group characteristics.

	"Naïve user group"	"Intermediate user group "	"Heavy user group "	p-value
Gender				0.758
F	51	52	47	
M	49	48	53	
Age (years)				0.170
Mean	31.67	29.70	28.47	
SD	11.79	13.00	11.45	
Education (years)				0.269
Mean	13.66	13.02	12.78	
SD	3.64	3.93	4.29	
Handedness (LQ)				0.299
Mean	86.32	89.22	89.50	
SD	18.00	14.31	15.43	
Clinic ID				0.241
Mean	2.66	2.75	3.08	
SD	1.89	1.74	1.91	
RUI ***				0.000
Mean	-	2.08	13.74	
SD	-	1.002	13.107	
Q4 ***				0.003
Mean	-	1.78	2.43	
SD	-	1.481	1.546	

Personality

In Table 2 the personality characteristics of the three groups are presented. There was one missing value due to incomplete data collection for the NEO FFI.

There was a significant difference between the groups on Extraversion (F= 4,407; df = 2, 296 p=.013) and Openness (F=3,520; df=2, 296; p=.031). The post hoc tests revealed that the Heavy User Group scored higher on Extraversion as compared to the Naïve User Group (P=.010). The post hoc tests for openness did not reveal further differences between the groups.

This difference in extraversion could reflect a cause of differences in mobile phone use rather then an effect, in the sense that heavy mobile phone users tend to be more extravert (e.g. business men, executives etc.) than naïve mobile phone users. Therefore, it was decided to use the scores on the NEO FFI extraversion and openness scales as co-variants in order to control for differences in personality profile. The statistics presented hereafter are therefore all co-varied for extraversion and openness.

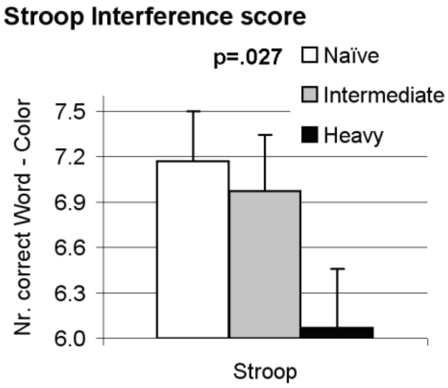
Table 2: NEO FFI results for the three groups

	"Naïve user group"	"Intermediate user group "	"Heavy user group "	p-value
N =	100	99	100	
Neuroticism				0.906
Mean	18.90	18.54	18.89	
SD	6.30	6.70	6.79	
Extraversion *****				0.013
Mean	29.04	30.44	31.35	
SD	4.90	5.77	5.91	
Openness *****				0.031
Mean	31.60	31.44	29.56	
SD	6.56	6.15	5.38	
Agreeableness				0.650
Mean	31.69	31.83	30.69	
SD	6.22	5.83	5.66	
Conscientiousness				0.552
Mean	30.59	31.70	31.14	
SD	7.28	7.44	6.26	

Neuropsychology

These results are presented in Figure 1. Multivariate GLM showed a group effect on overall neuropsychological performance (F=1.763; df=18, 574; p=.026) between the three user-groups (all neuropsychological measures mentioned under 'neuropsychology' were included in the analysis). Univariate ANOVA's revealed that there was a significant effect on the Word Interference score (F=3.654, df=2, 294 p=.027) and a near significant effect on the reverse digit span test (F=2.427, df=2, 294 p=.090) between the user groups. Post-hoc tests failed to reach significance and no significant differences were found between the user groups on the other neuropsychological indices.

Figure I: This figure shows the difference on the Stroop interference score between the three groups. Heavy mobile phone users show less interference on the Stroop test.



EEG

Since no differences in total absolute EEG power were observed, only the absolute EEG power data will be used. Relative power data were not analysed.

In figure II an overview of all major EEG findings can be found.

Multivariate analysis revealed a significant effect of condition (EO/EC) (F=3,877; df=1, 293; p=.050), electrode location (F=9,798; df=2, 292; p<.000) and EEG frequency (F=3,571; df=3, 291; p=.014), while the factor Group did not reach significance. The following within subject interactions were found: Location X Extraversion (F=3,521; df=2, 292; p=.031) ; First-order interactions were found between Condition and EEG frequency band (F=2,843; df=3, 291; p=.038) and between EEG frequency and Group (F=2,252; df=6, 584; p=.037). The latter outcomes prompted us to analyse putative Group effects for the separate frequency bands.

Delta
Multivariate analysis revealed an effect of electrode location (F=12,078; df=2, 293; p<.000), a Group effect (F=4,570; df=2; 294; p=.011) and a Condition X Group interaction effect (F=4,467; df=2, 294; p=.012). The condition X Group interaction effect prompted us to separate the analyses for the Eyes Open and Eyes closed condition. Anyway, this interaction suggests a differential effect of mobile phone use on delta EEG during Eyes open and Eyes closed, with more delta power present during the eyes closed condition.

Eyes Closed
For Eyes Closed condition multivariate analysis revealed an effect of electrode location (F=7,163; df=2, 293; p=.001) and Group (F=5,223; df=2, 294; p=.006). Delta was higher at the Central sites as compared to the temporal sites. Post Hoc analysis revealed that the heavy user group had more delta than the naïve user group (p=.007).

Eyes Open
For Eyes Open condition multivariate analysis revealed an effect of electrode location (F=14,712; df=2, 293; p<.000) and Group (F=3,421; df=2, 294; p=.034). Delta was higher at the central sites as compared to the temporal sites. Post Hoc analysis revealed that the heavy user group had more delta than the naïve user group (p=.011).

Theta
Multivariate analysis revealed an effect of Condition (F=4,910; df=1, 294; p=.027), electrode position (F=12,102; df=2, 293; p<.000) and Group (F=3,552; df=2; 294; p=.030).Theta was higher at the central sites as compared to the temporal sites and theta was also higher during eyes closed condition. Post Hoc analysis revealed that the heavy user group differed from the naïve user group (p=.023).

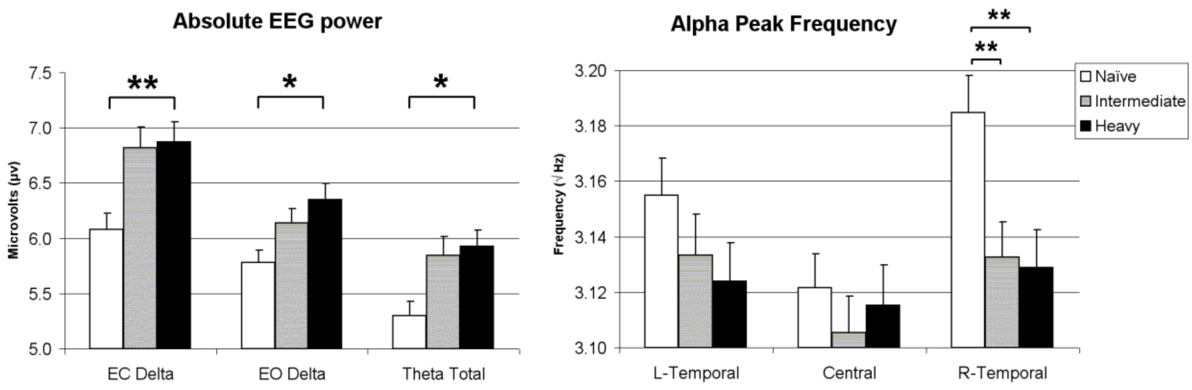
Alpha and beta
Multivariate analysis revealed only a location effect (F=4,163; df=2, 293; p=.016) for alpha power (increased alpha power at central sites as compared to temporal sites) and no effects for beta.

Alpha Peak Frequency
There were some missing values due to program failures to automatically detect a peak in the alpha frequency range in some cases'. Therefore, the number of subjects included the analysis was smaller than for the analyses of the power spectra. The number of subjects was 90, 85 and 84 for the naïve, intermediate, and heavy users respectively.

Multivariate analysis revealed only an electrode location X Group interaction (F=3,368; df=4; 508; p=.010). This interaction suggests that the effects of mobile phone usage on alpha peak frequency differ for the three locations. This prompted us to test whether there were group effects at the various electrode positions.

There were no significant group effects at left temporal nor at the central site, only at the right temporal site (F=5,240; df=2; 269; p=.006) differences were found. Post hoc tests showed that the naïve user group had a higher peak frequency than the heavy user group (p=.006) and the intermediate user group (p=.005).

Figure II: The figure below shows the findings for the EEG data. Note that all observed differences show dose-response like profiles (* p< .05; ** p<.010; EC and EC stand for Eyes Closed and Eyes Open condition).



<u>ERP</u>
For ERP variables there were missing values due to the fact that P2 and N2 components could not always be reliably scored. Group sizes used for this analysis are therefore: N=75 for Naïve; N=77 for Intermediate and N=60 for Heavy GSM users.

Multivariate analysis revealed an effect of ERP variables (F=270,318; df=7, 201; p<.000) showing that latencies and amplitudes of the different components are different and an ERP X electrode location interaction (F=4,216; df=14, 194; p<.000) indicating that the different ERP components had differential effects on the three electrode locations. However, no effect of Group (F=1,319; df=2; 207; p=.270) could be found.

<u>Interactions with Personality</u>
The MANOVA's also revealed now and than significant interactions with EEG variables and scores on the Extroversion and Openness dimension. For EEG variables a Location X Extraversion (F=3,521; df=2, 292; p=.031), a Condition X EEG frequency band X Extraversion (F=3,004; df=3, 291; p=.031) and Condition X EEG frequency band X Openness (F=3.641; df=3, 291; p=.013) interaction effect was found. For delta power a Location X Extraversion interaction (F=3,278; df=2, 293; p=.039) was found.
The MANOVA's on the alpha peak frequency revealed an electrode position X Extraversion interaction (F=4,097; df=2, 293; p=.018) and between Condition x Openness (F=4,744; df=1; 254; p=.030). At the right temporal location a Condition X Openness interaction (F=4,142; df=1; 269; p=.043) was found.

Although of interest for explaining individual differences in EEG related variables, these interactions are not further analyzed here since they are beyond the scope of the present research question. However they suggest that there are small relations between personality and EEG related variables.

Discussion

Heavy mobile phone users were found to be more extraverted and open as compared to naïve mobile phone users. These findings suggest that heavy mobile phone users have a different personality profile as compared to naïve mobile phone users. We see no reason this finding could be interpreted as being a direct effect of mobile phone use on brain function. Therefore it can be supposed that this finding merely reflects a pre-existing difference between heavy and naïve GSM users and could be explained by the fact that some people e.g. executives, salesmen, women etc. use mobile phones more frequently. These jobs (executives, salesmen) also require a different set of personality traits. Furthermore, it can be expected that extraverted people tend to communicate more with other people as compared to introverted people, and therefore extraverted people use mobile phones more often.

An overall effect of mobile phone use on cognition was found. Heavy mobile phone users perform better on the Word Interference test and tended to perform worse on the reverse digit span test. Heavy mobile phone users tend to experience less interference on the color condition. It could therefore be suggested that heavy mobile phone users have better focused attention than naïve users.

It is interesting to note that several studies have found that acute exposure to EMF tended to increase performance on attention tests as well (Lee et al., 2001; 2003; Koivisto et al., in press). In these studies it was hypothesized that the increased performance on attention was due to a local increase in temperature by EMF. In the current study, subjects were not exposed to EMF, so therefore this finding cannot be attributed to an increase in temperature. Furthermore, the Stroop and perhaps our version of the Word Interference test can be regarded as a frontal task (for review see MacLeod, 1991), and therefore there is no simple reason to attribute the improved scores on the Word Interference score directly to the effects of stimulation of the right or left temporal cortex (where the mobile phone is held) - if localized effects of EMF were expected. Therefore it is not likely that this finding is related to EMF exposure on the brain, which is also supported by the fact that we did not find any effects on ERP latencies and amplitudes. Another explanation could be that heavy mobile phone users often make phone calls in busy environments (e.g. in a train, shop, street) which requires the user to focus his attention on the phone conversation and filter out irrelevant environmental information. In this way heavy mobile phone users train their focused attention, and therefore perform better on the Word Interference test. A similar - training explanation - could be used for the near significant finding on the reverse digit span, since heavy mobile phone users often pre-program all phone numbers in the phonebook of the cell phone. Therefore, heavy mobile phone users train their span-memory less and tend to perform worse on the reverse digit span test.

Heavy mobile phone users show increased delta and theta EEG activity, during both eyes open and eyes closed over all three regions. Furthermore, heavy mobile phone users showed a decreased alpha peak frequency at the right temporal region. These finding suggest a general slowing of the EEG (increase in slow EEG activity, decreased EEG peak frequency) originating at the right temporal region. The fact that delta and theta were found to be increased over all three sites could be explained by the fact that low frequencies usually spread widely over the cortex.

Only right handed people were included in the analysis. However, we had no information as to which hand our subjects used to hold their mobile phone. Moreover, some people do not consistently use the same hand since the usage of the left and right ear might also depends on whether a second task has to be fulfilled such as writing. Since we had detailed information on handedness (all subjects were assessed on Arnett's Handedness Questionnaire) we investigated in 36 people whether there is any relation between handedness and laterality of phone use. These results indicated that 56,25% of right handed people used their right hand, 31,25% used their left hand and 12,5% used both hands to hold their phone. No clear relation could be established between any of the items on the questionnaire and laterality of phone use. Rothman et al. (1996) also failed to find an association between handedness and laterality of phone use. Since most right handed people hold their mobile phone on the right it seems therefore likely that the decrease in alpha peak frequency at the right temporal region is directly associated with EMF exposure due to the frequent use of mobile phones. This is further strengthened by the finding that most measures show gradual differences between naïve, intermediate and heavy GSM users. This suggests that the differences between the groups could indeed be related to the amount of mobile phone usage.

Some studies have sought to establish a relation between personality and EEG measures. For example Stough et al. (2001) found a positive correlation between theta EEG power and openness for all cortical regions (in contrast to our results where heavy mobile phones users scored lower on openness but had greater overall theta EEG. Correlations between theta power and openness were also found to be negative from our data). Tran, Craig and McIsaac (2001) found that extraverted people showed increased alpha power at frontal regions. No associations could be found for posterior regions. And finally, Schmidtke and Heller (2003) found a negative correlation between alpha power at T5 and T6 and neuroticism, but no correlations for extraversion. Furthermore, we have co varied for the pre-existing differences in extraversion and openness. Therefore, it is not likely that the observed findings on EEG variables are due to the pre-existing differences in personality profile, suggesting that the observed findings could relate directly to EMF exposure due to mobile phone use.

This study also had some limitations. The information concerning mobile phone usage was limited, and future studies would do well to check the self-reported information of phone usage by subjects against their phone bills. We also did not know whether subjects used headsets or car kits and to what extent. However, it is not unreasonable to assume that, considering the large sample size, these inaccuracies have averaged out and do not preferentially influence one of the groups of users.

Previous studies investigating acute EMF effects employing EEG have most consistently found an increase in alpha EEG activity, mainly in the parietal and occipital areas of the brain (Waking EEG: Croft et al., 2002; Schulze et al.; Mann & Röschke, 1996; Krause et al., 2000; Polysomnographic EEG: Lebedeva et al., 2001; Borbely et al., 1999; Huber et al., 200, 2002 a, 2002 b). Results from previous studies are somewhat inconsistent with respect to delta, theta and alpha peak frequency. Croft et al. (2002) found a decrease in delta power during EMF exposure whereas Kramarenko and Tan (2003) found small bursts of slow waves in the delta – theta range after 15-20 seconds of mobile phone use. In the studies of Huber et al. (2000) and Borbely et al. (1999) alpha peak frequency was not affected. However, Kramarenko and Tan (2003) found an increase in the median EEG frequency. These effects were found during – or directly after – acute exposure to EMF. Therefore it is hard to compare our findings to these studies, since we found a long term effect, even present in absence of EMF.

As Kramarenko and Tan (2003) indicated, an increase in delta and theta during waking can be regarded as abnormal for healthy subjects. Furthermore, EEG slowing has often been associated with pathological conditions such as Alzheimer's (Rodriguez et al., 1999) and extensive brain damage. The increase in absolute delta power for eyes closed and eyes open was 13,1 % and 9,8% respectively, absolute theta power was increased with 11,8% and right temporal alpha peak frequency was decreased with only 1,8 %. These values were still within physiological limits and cannot be considered pathological. Furthermore, since no effects on cognition are found, it seems that the observed changes in brain function have no functional relevance (yet). It is therefore difficult to draw any conclusions about the biological and clinical relevance of these findings. The heavy user group in this study had an average score of 2,4 on usage in years, representing an average use of approximately 2-3 years. From a cautionary point of view it therefore needs to be stressed that more research is needed to establish whether these effects should be interpreted as adverse health effects with the following question in mind: "If these changes can already be found after 2-3 years of mobile phone use, what could be the effects after 5-10 years of mobile phone use?"

Most studies and health authorities have concluded that the main EMF-biological tissue interaction consists of heat exchange (IEGMP, 2000; Health Council, 2002). If the findings from the present study are due to thermal effects only, local effects can be expected (since the effect of heat exchange diminishes exponentially over distance). We only found a local effect for the right temporal region, but also an overall effect for delta and theta. The fact that delta and theta were elevated over all three areas can be explained by the fact that these are relatively low frequencies, thereby spreading over a bigger distance over the cortex. In the light of this hypothesis it could then be expected that heavy mobile phone use might have led to underlying functional or structural abnormalities, potentially explaining the EEG slowing originating from this area. It has to be noted, however, that it seems rather unlikely that changes in brain temperature in the order of 0.12 degrees Celsius (van Leeuwen et al., 1999; Bernardi, et al., 2000; Wainwright, 2000; Wang & Fujiwara, 1999) have these kind of long term effects. In that case a simple fever of 40 degrees Celsius (increase of 3 degrees Celsius) would have more impact on brain function.

Two recent studies both suggest non-thermal effects in the explanation of altered brain activity. Huber et al. (2002) found that usage of mobile phones alters regional cerebral blood flow in the dorsolateral prefrontal cortex of the exposed hemisphere (and not in the temporal regions). Furthermore, they compared the effects of a pulse modulated signal (GSM signal) to a continuous signal with the same characteristics, and found that pulse modulation was critical for their frequently reported EMF changes in brain function, ruling out the thermal effect, which was equal for both signals. From the Kramarenko and Tan (2003) study it was found that the occurrence of slow wave bursts was mainly located at the exposed temporal region but also at F7 and to a lesser extent at F8 (overlaying the dorsolateral prefrontal cortex). They conclude that EMF have a direct effect on brain function and cannot be explained by a thermoregulatory effect in agreement with the conclusions from Huber et al. (2002). The dorsolateral prefrontal cortex has been implicated in working memory (Wagner et al. 2001). If this non-thermal effect of EMF is taken into account it could well be that the near significant effect on the reverse digit span - and to a lesser extent the Word Interference finding – could be explained by the effects on the dorsolateral prefrontal cortex. However, this study is too limited to currently support this hypothesis. In order to further investigate this hypothesis future – database driven – studies should include frontal sites and also include the results from more executive or frontal tests (e.g. executive maze test).

In order to further investigate the presence of underlying structural or functional abnormalities one could investigate sMRI and fMRI data in a similar manner. In the International Brain Database we currently have subjects who have been assessed on sMRI and fMRI, besides psychophysiological and neuropsychological assessments. Future studies could inspect these data and see whether any functional or structural changes can be found in the temporal regions of heavy mobile phone users as compared to naïve users, and whether the findings from this study correlate to sMRI and/or fMRI results.

Conclusion

Note that the presented findings represent statistical findings, and can therefore not be interpreted as causal findings. These findings will be further discussed with collaborators and other experts in order to reach a final interpretation and conclusion. Therefore, the conclusion and interpretation of these findings will be further worked out in forthcoming publications.

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