
ELECTROENCEPHALOGRAPHIC, PERSONALITY, AND EXECUTIVE FUNCTION MEASURES ASSOCIATED WITH FREQUENT MOBILE PHONE USE

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The present study employs standardized data acquired from the Brain Resource International Database to study the relationship between mobile phone usage, personality, and brain function ($n = 300$). Based on the frequency and duration of mobile phone usage, three groups were formed. The findings suggest a subtle slowing of brain activity related to mobile phone use that is not explained by differences in personality. These changes are still within normal physiological ranges. Better executive function in mobile phone users may reflect more focused attention, possibly associated with a *cognitive training* effect (i.e., frequently making phone calls in distracting places), rather than a direct effect of mobile phone use on cognition.

Keywords cognition, EEG slowing, GSM, mobile phone, neuropsychology, personality

INTRODUCTION

Industry sources suggested that there will be over one billion mobile phone (MP) users worldwide by 2005 (Repacholi, 2001). Reviews of the effects on general health, including carcinogenic potency, of the 900–1800 MHz electromagnetic fields (EMF) emitted by MPs find no significant adverse affects (the Dutch Health Council, 2002; Independent Expert Group on Mobile Phones [IEGMP], 2000). Three primary theories of the potential effects of EMF on biological tissue are (1) the activation of endogenous opioids; (2) the induction of electrical fields in the brain; and (3) thermal radiation (Banik et al., 2003). To date little experimental evidence is available to support the former two theories (Repacholi, 2001). However, studies suggest EMF produced by MP may cause a change in temperature of biological tissue (van Leeuwen et al., 1999). The radiation produced by MP changes the skin's temperature by .25 degrees and the brain's temperature by .12 degrees Celsius. However, this is suggested to have no real effects on health (van Leeuwen et al., 1999; Bernardi et al., 2000; Wainwright, 2000; Wang & Fujiwara, 1999). Nevertheless, given that phones are often used in close proximity to the head, it is important to investigate whether long-term and/or frequent MP use have any specific effects on brain function through heat radiation or otherwise.

The direct effects of MP-use *during* use (i.e., acute effects) on brain function have been investigated using neuropsychological and neurophysiological techniques. Evidence suggests an association between acute MP use and enhanced scores on cognitive tests. For example, exposure to a field that simulates MP use decreases reaction times (Preece et al., 1999; Koivisto et al., 2000) and enhances performance in attention tasks without an increase in the

number of errors made (Lee et al., 2001; 2003; Koivisto et al., 2000). These results have been mostly interpreted as being due to small increases in brain temperature that lead to increased metabolic activity and thus faster reaction times. Thus, EMF may also have potentially beneficial effects on brain function that could be developed as treatment for functional brain disorders.

Electroencephalographic (EEG) studies show an increase in alpha EEG power, mainly in the parietal and occipital areas during exposure to a MP-“like” field; during wakefulness (Croft et al., 2002; Schulze et al. 1996; Mann & Röschke, 1996; Krause et al., 2000) and sleep (Lebedeva et al., 2001; Borbély et al., 1999; Huber et al., 2000; 2002a; 2002b). Furthermore, increases in theta power (Lebedeva et al., 2001) and modulation of high frequency induced brain activity (Eulitz et al., 1998) have been reported during MP exposure. In contrast, other studies find no significant effects of MP exposure on spectral measures of the wake and sleep EEG (Röschke & Mann, 1997; Wagner et al., 2000; Eulitz et al., 1998). In more controlled studies, Krause et al. (2004) and Haarala et al. (2003) failed to replicate previous findings. Thus, if present, the acute effects of MP-use on EEG, memory or reaction time may be small, variable and not easily replicable. Thus, results of the acute effects of an MP-“like” field on brain function are inconclusive and reasons for the aforementioned inconsistencies are unclear.

The relationship between the cumulative long-term and/or frequent use of MP use on brain function and information processing has not been reported. Such a study would require an expensive, complex longitudinal study. Given current inconsistencies in the aforementioned studies of acute effects, it is unclear whether such expense would be warranted. Therefore, the current epidemiological study was designed to gather pilot data and explore the association between long-term and/or frequent MP-use, brain function, and personality. Thus, the Brain Resource International Database (also see www.brainnet.org.au) was used to investigate personality, neuropsychological performance, and brain function as a function of self-reported mobile phone use in a large group of healthy subjects. In addition, the current study aimed to identify appropriate measures of brain function and/or possible confounding variables associated with long-term regular MP use that could be incorporated into a future study.

MATERIALS AND METHODS

Subjects

Three hundred right-handed healthy individuals were used in this study (see Table 1 for subject characteristics). Database exclusion criteria included

Table 1. Group characteristics

	"Naïve MP user group"	"Intermediate MP user group"	"Heavy MP user group"	<i>p</i> -value
Gender				0.756
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	
RUI***				0.000
Mean	—	2.08	13.74	
SD	—	1.002	13.107	

a personal or family history of mental illness, brain injury, neurological disorder, serious medical condition, drug/alcohol addiction; and a family history of genetic disorder. Six laboratories (New York, Rhode Island, Nijmegen, London, Adelaide, and Sydney) participated using standardized data acquisition techniques (identical amplifiers, standardization of other hardware, paradigm details, software acquisition, and task instructions). Interlab reliability measures were high and are reported elsewhere. All subjects voluntarily gave written informed consent, and local medical ethical approval was obtained for all clinics. Subjects were required to refrain from caffeine, alcohol, and smoking for at least 2 h prior to testing.

Grouping of Participants According to Mobile Phone Use

Table 2 shows the self-report questionnaire used to quantify the extent of mobile phone use by participants. This questionnaire was developed as part of the Brain Resource International Database. Currently reliability and validity data for this questionnaire are not available. A measure of Recent Usage Intensity (RUI) was computed based on number of phone calls per day (question 1) \times duration of phone calls (question 2) \times total time of mobile phone use (question 3). Three MP user groups of equal size ($n = 100$) were formed based on the RUI. The top-100 users were identified *Heavy-users*. A *Naïve user* group consisted of 100 subjects who answered Q0 with "no" (did not use mobile phone). An *Intermediate-user* group consisted of 100 subjects randomly

Table 2. Self-report questionnaire used to quantify the extent of mobile phone use by subjects

Question	Answer
Q0: Do you use a mobile phone?	Yes/no
Q1. How often do you use a mobile phone (to make or receive a call)?	(5) Many times a day (4) A few times a day (3) Once a day (2) Once every few days (1) 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?	(5) Less than 1 year (4) 1–2 years (3) 2–3 years (2) 3–5 years (1) Greater than 5 years

Scores for the individual answers are between brackets.

selected from the remaining subjects who answered Q0 with “yes.” Table 1 shows the demographic characteristics of the subjects included in the study.

Subjects were seated in a sound and light attenuated room, controlled at an ambient temperature of 22°C. Personality, electroencephalographic, and neuropsychology assessments were completed in order.

Personality

NEO–FFI (Five Factor Inventory) (Costa & McCrae, 1992) was used to measure five personality traits including conscientiousness, agreeableness, neuroticism, extraversion, and openness.

Electroencephalographic Data Acquisition

Participants were seated in a sound and light attenuated room, controlled at an ambient temperature of 22°C. EEG data were acquired from 28 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 (Quikcap; NuAmps; 10–20 electrode international system). Data were referenced to linked mastoids with a ground at AFz. Horizontal eye-movements were recorded with electrodes placed 1.5 cm lateral to the outer canthus of each eye. Vertical eye movements were recorded with electrodes placed 3 mm above the middle of the left eyebrow and 1.5 cm below the middle of the left bottom eye-lid. Skin resistance was < 5 K Ohms and above 1 K Ohm 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 40 dB per decade above 100 Hz was employed prior to digitization.

The EEG data were recorded for 2 min during each of two conditions: eyes open (EO) and eyes closed (EC). Subjects were asked to sit quietly. During EO subject were asked to fix their eyes on a red dot presented on a computer screen.

Electroencephalographic Variables

Average power spectra were computed for each condition (EO, EC). Each two minute epoch was 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 power was calculated in the four frequency bands for both conditions, delta (1.5–3.5 Hz), theta (4–7.5 Hz), alpha (8–13 Hz), and beta (14.5–30 Hz). These power data were then square-root transformed in order to fulfill the normal distributional assumptions required for parametric statistical analysis.

Electrode Sites

Given that right (T4, T6) and left temporal (T3, T5) areas are in close proximity to the ears and therefore more susceptible to the effects of MP use, EEG measures were taken from these areas. However, midline areas (FCz, Cz, CPz, Pz) were also examined as a measure of overall brain function. Data from other sites were not examined in the current study.

Alpha peak frequency data were scored using a robust algorithm and manually checked by an independent scorer.

Neuropsychology

Neuropsychological assessment was completed using a touch screen monitor. Measures included: Visual working memory, Digit Span (forward and reverse),

Table 3. Neuropsychological tests assessed and the according variables

Task	Measure
Visual span of attention	Number correct
Digit span	Number correct
Reverse digit span	Number correct
Word interference	Number correct for word condition; number correct for color condition, <i>word interference score</i> (number correct for word condition—number correct for color condition)
Switching of attention test (A and B)	Number completed, number of errors

Word Interference test (equivalent to the Stroop test), and Switching of Attention test part A and B (equivalent to the WAIS Trails A and B) (see Gordon, 2003 and Gordon et al., 2005 for details of these tests). All tests were fully computerized and subjects' responses were recorded via touch-screen presses. Reliability and validity data on these tasks are reported elsewhere (Gordon et al., 2005; Clark et al., 2006; Williams et al., 2005; Paul et al., 2005). Variables measured by each test are displayed in Table 3.

STATISTICAL ANALYSIS

Missing Values

If missing values were present for a given statistical test, those cases were excluded for that analysis. The number of missing values per group are included in the Results sections.

Analysis

All statistics were performed using SPSS 11.5.1 for Windows. Differences between RUI groups in age, education, and personality scores were tested using one-way Analyses of Variance (ANOVA). Bonferroni tests were used for post-hoc analysis. Differences between groups in categorical variables (Sex and RUI) were tested using Kruskal-Wallis nonparametric test.

Multivariate Analysis of Variance (MANOVA, Pillai's Trace) were used to test for group differences in scores on neuropsychology tests with RUI as a between groups variable and neuropsychology tests as a within subjects variable. Bonferroni tests were used in post-hoc analysis. Univariate ANOVAs were then used to test for differences between RUI groups on individual tests.

Any significant differences in personality profile were taken into account by including these measures as covariates in these MANOVAs and ANOVAs

EEG Data

MANOVA (using Pillai's Trace) was used to test group differences in power with the within groups variables *Task* (EO/ EC), *Electrode Location* (Left Temporal, Central, and Right Temporal) and *Frequency Band* (delta, theta, alpha, and beta) and between groups variable *RUI Group* (Naïve, Intermediate, and Heavy user group). Significant interactions were further explored using within-group MANOVAs, and via simple contrasts for the between subject factor. Alpha peak frequency was analyzed in the same way, replacing EEG frequency with alpha peak frequency. As with neuropsychology analyses, any significant differences in personality profile were taken into account by including these measures as covariates.

RESULTS

Table 1 shows means, *SDs*, and *p* values of sex, age, education, and RUI naïve, intermediate, and heavy users. There were no differences between the three groups with respect to age, sex, and education. However, there were differences between the groups for mobile phone use (RUI), indicating that the groups differed only in mobile phone use and not on other variables such as age, sex, and years of education.

Personality

Table 4 displays the personality characteristics of the three groups. There was one missing value (.33%) due to incomplete data acquisition of the NEO FFI.

There was a significant main effect of *MP group* for Extraversion ($F = 4.407$; $df = 2, 296$ $p = .013$) and Openness ($F = 3.520$; $df = 2, 296$; $p = .031$). Pair wise contrasts revealed that the Heavy User Group scored higher on Extraversion as compared to the Naïve User Group ($p = .010$). No significant differences were seen in contrasts for openness. Therefore, Extraversion and Openness were used as covariates in further analyses as described in the following sections.

Neuropsychology

Significant findings for neuropsychology variables are presented in Figure 1. A significant difference was seen for *RUI group* in overall neuropsychological

Table 4. NEO FFI results for the three groups (Costa & McCrae, 1992)

	"Naïve user group"	"Intermediate user group"	"Heavy user group"	<i>p</i> -value
<i>n</i> =	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	

performance ($F = 1.763$; $df = 18, 574$; $p = .026$). Univariate ANOVA's revealed that there was a significant effect on the Word Interference Score ($F = 3.654$, $df = 2, 294$, $p = .027$) with the heavy user group showing the highest interference score, (i.e., least interference). However, post-hoc tests

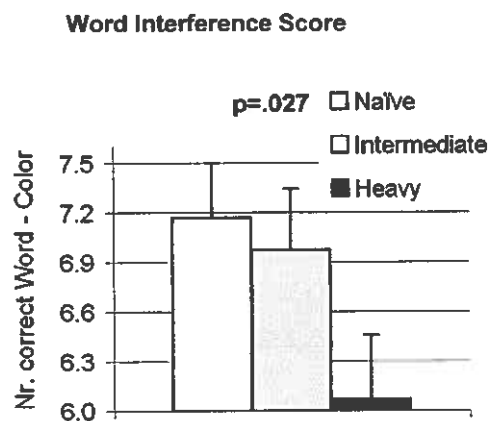


Figure 1. Difference on the Word Interference Score between the three MP user groups. Heavy mobile phone users show less interference than the other two groups (error bars are S.E.M.).

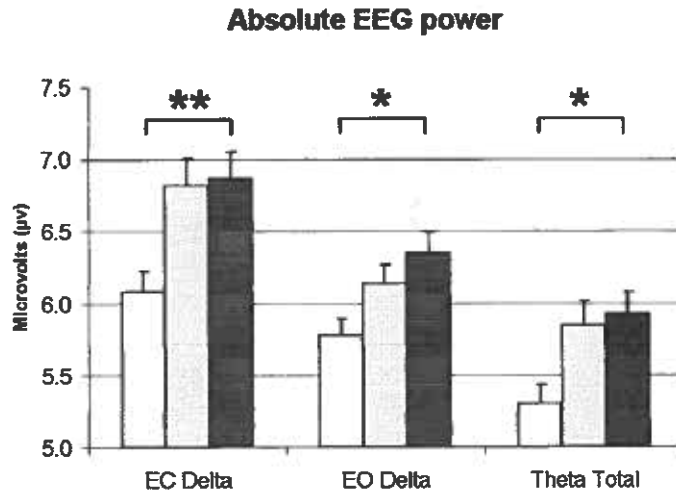


Figure 2. Findings for the EEG data across the groups. Note that all observed differences show dose-response like profiles (* $p < .05$; ** $p < .010$; *** $p = .001$). EC and EO stand for eyes-closed and eyes-open condition).

failed to reach significance. No significant differences were found between the user groups on any other neuropsychology measures.

EEG

Figure 2 shows the significant findings for Delta power (during Eyes Closed and Eyes Open) and Theta Power (average for Eyes open and Eyes Closed). Figure 3 shows mean alpha peak frequency for EO and EC at left temporal, central, and right temporal sites. Figure 4 shows the significant findings for mean alpha peak frequency for EO (average of combined sites).

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 ($F = 3.571$; $df = 3, 291$; $p = .014$). There was no significant main effect for RUI. The Location X Extraversion interaction was significant ($F = 3.521$; $df = 2, 292$; $p = .031$). Significant first-order interactions were found between Condition and EEG frequency band ($F = 2.843$; $df = 3, 291$; $p = .038$) and between EEG frequency and RUI group ($F = 2.252$; $df = 6, 584$; $p = .037$). RUI group effects for the separate frequency bands are reported in what follows.

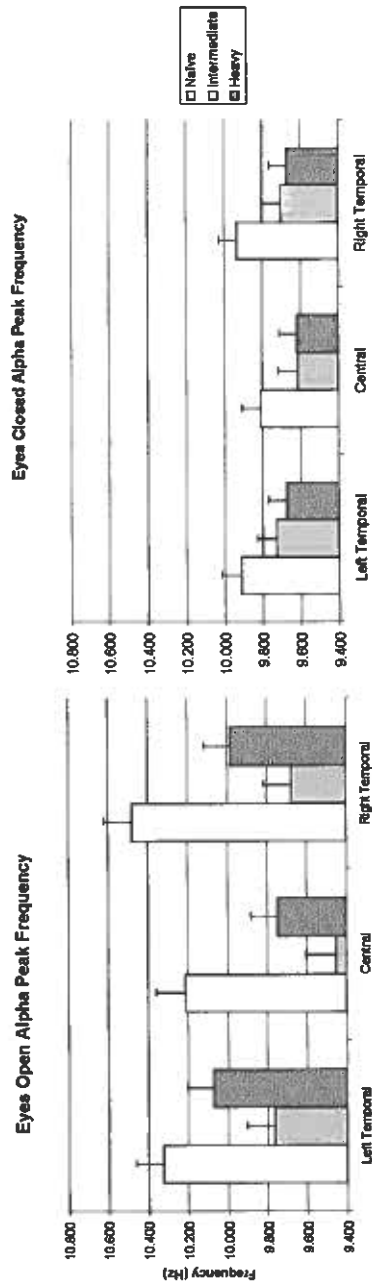


Figure 3. The consistent decreased peak alpha frequency for the mobile phone user groups compared to naive users for the three locations. Note the fact that during eyes open EEG the alpha peak frequency for both mobile phone user groups is decreased, but only for the intermediate group significantly so. Correlational analysis revealed that the alpha peak frequency correlated significantly to RUI, thereby supporting the fact that this effect is related to mobile phone use.

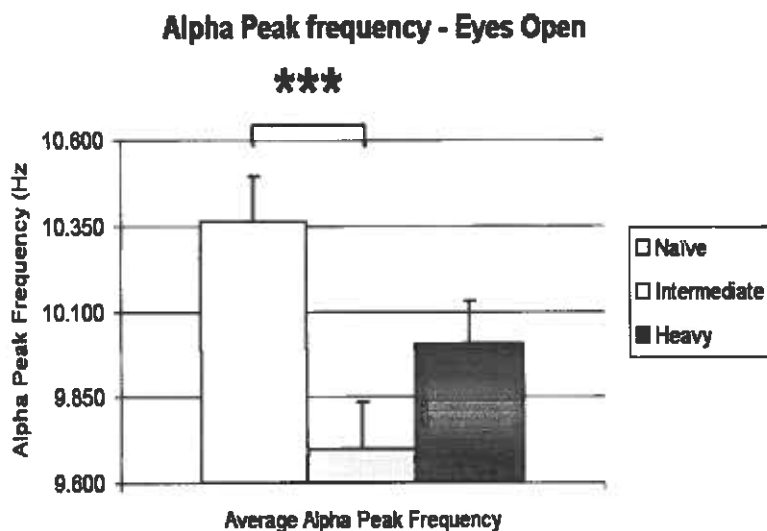


Figure 4. Significant effect for alpha peak frequency during eyes open EEG.

Delta

Significant differences in delta power were found for electrode location ($F = 12.078$; $df = 2, 293$; $p < .000$) and RUI ($F = 4.570$; $df = 2, 294$; $p = .011$). A significant interaction was seen for Condition X RUI group ($F = 4.467$; $df = 2, 294$; $p = .012$). Thus, separate analyses were performed for EO and EC.

Eyes Closed—Delta. For the eyes-closed condition MANOVA 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. Contrasts revealed that the heavy user group had more delta than the naïve user group ($p = .007$).

Eyes Open—Delta. For the eyes-open condition MANOVA 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. Contrasts 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

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($F = 3.552$; $df = 2$; 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. Contrasts revealed that the heavy user group differed from the naïve user group ($p = .023$), with the heavy user group showing increased theta power.

Alpha and Beta

Multivariate analysis revealed a significant effect of Location ($F = 4.163$; $df = 2$, 293 ; $p = .016$) for alpha power. Alpha power was increased at central compared to temporal sites. No significant effects were seen for beta.

Alpha Peak Frequency

Figure 3 shows the results for alpha peak frequency for all three locations during both eyes-open and eyes-closed condition. Figure 4 shows the significant findings for alpha peak frequency during eyes-open.

The following percentages of missing values were reported for this analysis naïve 14%; intermediate 18% and heavy 19%. The main effect for RUI was close to significance ($F = 2.957$; $df = 2$; $p = .054$). Multivariate analysis revealed a significant interaction between Condition and RUI ($F = 3.452$; $df = 2$; 244 ; $p = .033$). EO and EC conditions were therefore analyzed separately.

Eyes Closed

The following percentages of missing values were reported for this analysis: naïve 5%; intermediate 7%; and heavy 6%. Multivariate analysis showed no significant effect for RUI group ($F = 1.491$; $df = 1$; $p = .227$).

Eyes Open

The following percentages of missing values were reported for this analysis: naïve 12%; intermediate 15%; and heavy 16%. MANOVA revealed a significant effect for RUI group ($F = 5.986$; $df = 2$; $p = .003$). Post hoc analysis demonstrated that the naïve group had significantly higher alpha peak frequency compared to the intermediate group ($p = .001$), but did not significantly differ from the heavy user group ($p = .106$).

Bivariate non-parametric correlations (Kendall's tau.b) revealed a significant correlation between RUI score and eyes-open alpha peak frequency at

central ($r = -.093$, $p = .028$) and right ($r = -.114$, $p = .009$) areas and between right-temporal eyes-open alpha peak frequency and Openness ($r = .084$; $p = .044$). The correlation was not significant between eyes-open alpha peak frequency and NEO FFI scores, education, age, sex, or neuropsychological indices of executive function.

DISCUSSION

This pilot study sought to investigate the relationship between long-term MP use and brain function employing an epidemiological approach. MP-use was associated with EEG slowing as demonstrated by increased delta and theta power and decreased alpha peak frequency in MP users. Furthermore, heavy MP use was associated with less interference on the word interference test, as well as increased extraversion and decreased openness.

Increased delta and theta EEG activity were observed during both eyes open and eyes closed conditions over all three regions in participants who reported heavy usage of mobile phones. The data used in this study were all EOG corrected, therefore these increases in Theta and Delta cannot be explained by differences in eye movements or EOG artefacts. Both mobile phone user groups, compared to naïve users, showed decreased alpha peak frequency—only significantly so for the intermediate user group—particularly during eyes-closed condition. This suggests a general slowing of the EEG, related to mobile phone use (increase in slow EEG activity, decreased EEG peak frequency). Figure 3 shows that the decrease in alpha peak frequency during eyes-open is more pronounced for the intermediate group than the heavy group. Therefore, it could be questioned whether this effect is really related to mobile phone use. However, a highly significant negative correlation was seen between RUI and eyes-open alpha peak frequency for the central and right temporal regions. Indeed, the study also found a correlation between Openness and eyes-open alpha peak frequency; however, this correlation was less significant, smaller and only present for the right temporal region. The fact that eyes-open alpha peak frequency did not significantly correlate with other NEO FFI scores or the interference score further adds to this. Therefore, these effects cannot easily be explained by differences between groups in personality or neuropsychological results. Nor are they likely to be due to education or age, as groups did not significantly differ on these variables. Thus, an association between MP-use and alpha peak frequency is supported. However, it is difficult to draw firm conclusions about causality in the current

study, which was epidemiological and used self-reported questionnaires of MP-use rather than directly measuring EMF exposure levels.

Heavy mobile phone users performed better on the Word Interference test, a measure of executive function. Results suggest heavy mobile phone users experience less interference on the color condition, reflecting better executive function. This supports previous studies that report an increase in performance on attention tests with acute exposure to MPs (Lee et al., 2001; 2003; Koivisto et al., 2000; Krause et al., 2000b). These studies suggest increased performance on attention may be due to an acute local increase in temperature by EMFs emitted by the MP. However, in the current epidemiological study subjects were not acutely exposed to a MP. Therefore, results cannot be attributed to an acute increase in temperature. Current results suggest that, as well as the acute effects seen in previous experimental studies, chronic changes in neuropsychological performance are associated with increased MP use. Future studies should explore whether these are due to EMF exposure or some other as yet unknown variable. For example, heavy mobile phone users may more often make phone calls in busy environments (e.g., in a train, shop, street), which would require focused attention on the conversation while filtering out irrelevant environmental information. This may act as a kind of cognitive training that could have the effect of enhancing focused attention. Alternatively, people who are able to focus on using the phone in busy environments may be more likely to use phones frequently. Longitudinal studies are required to confirm the causal direction of the relationship between control of attention and frequent MP use. Other tasks and modalities used to measure controlled attention (e.g., P300 event-related potential) could also be used to understand the current results better.

Finally, heavy mobile phone users were found to be more extraverted and less open compared to naïve mobile phone users. This finding probably reflects a preexisting trait difference between heavy and naïve MP users, and could reflect the fact that some jobs (e.g., executives, salesmen) use mobile phones more frequently. It can also be expected that extraverts tend to communicate more often with other people compared to introverts, which could involve frequent mobile phones use.

Some studies have sought to establish a relationship 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, a negative correlation was found between theta power and Openness in the current study. The results also show heavy mobile phones users scored lower on Openness but had greater overall theta EEG. Tran et al. (2001) found that extraverts showed increased alpha power in frontal but not posterior regions.

Schmidtke and Heller (2004) found a negative correlation between alpha power at T5 and T6 and neuroticism, but no correlations for Extraversion. The present authors have covaried for the preexisting differences in Extraversion and Openness. This, together with the earlier summarized findings makes it implausible that personality alone could have accounted for the relationship between mobile use and EEG in the current study.

Previous studies investigating acute EMF effects on EEG have most consistently found an increase in alpha EEG activity (Waking EEG: Croft et al., 2002; Schulze et al., 1996; Mann & Röschke, 1996; Krause et al., 2000; Lebedeva et al., 2001; Borbély et al., 1999; Huber et al., 2000, 2002a, 2002b). Results from lower frequencies are less consistent. Croft et al. (2002) found a decrease in delta power during EMF exposure. However, Kramarenko and Tan (2003) found small bursts of slow waves in the delta–theta range after 15–20 s of mobile phone use that is consistent with the increase in delta and theta seen in the current study. Huber et al. (2000) and Borbély et al. (1999) found no effect in alpha peak frequency in response to acute EMF exposure. However, Kramarenko and Tan (2003) found an increase in the median EEG frequency. It could be speculated that although increases in EEG frequency are seen in acute MP use, or in response to EMF exposure, decreases in resting EEG frequency may follow frequent use. Clearly, further studies investigating both acute and long-term frequent use should be conducted.

EEG slowing is seen in a number of pathological conditions including Alzheimer's (Rodriguez et al., 1999). However, the change in EEG power in the current study was small. The increase in delta power in MP users for eyes-closed and eyes-open was 13.1% and 9.8%, respectively; theta power was increased with 11.8%; and alpha peak frequency was decreased with 6.4% (intermediate user group) and 3.4% (heavy user group). Thus values reported in the current study are within normal variation and are not considered pathological.

Previous studies suggested that the main effect of EMF on biological tissue is due to heat exchange (IEGMP, 2000; Health Council, 2002; van Leeuwen et al., 1999; Bernardi, et al., 2000; Wainwright, 2000; Wang & Fujiwara, 1999). However, whether changes in brain temperature of this small magnitude have the kinds of long-term and widespread effects seen in the current study is yet to be confirmed. If the current findings are due to thermal effects, local effects would be expected, given that the effect of heat exchange diminishes exponentially over distance. However, the observed effects in this study were consistent over all areas (bilateral temporal and central areas).

Recent studies suggest alternative explanations of altered brain activity in response to MP use. Using PET scans, Huber et al. (2002) found that MP

use 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 (MP signal) to a continuous signal with the same characteristics, and found that pulse modulation was critical for reported EMF changes in brain function. Furthermore, their results suggest that changes were not due to a thermal effect, which was equal for both signals. Concordantly, although Kramarenko and Tan (2003) found a main effect over the exposed temporal regions, significant EEG slowing was also seen at F7 and F8, which may reflect dorsolateral prefrontal cortex function. This suggests that EMF has a direct effect on brain function, but cannot be explained by a thermoregulatory effect (Kramarenko & Tan, 2003). These studies only came to the authors' knowledge after the data analysis was finished, hence this article has not included frontal sites in the data analysis, because—at that time—there was no evidence for mechanisms other than thermal effects.

MPs are relatively new to the market. It is not surprising then that in the current study the average duration of having used a mobile phone was relatively brief in all groups (heavy users = 2.4 years; intermediate-users = 1.8 years). Although a causal relationship needs to be confirmed by future research, if the relationship between MP-use and brain function found in the current study is in fact due to EMF or some other aspect of MP-use, the question must be asked as to how these effects would change over a period of 5 or even 10 years of use. A follow-up study investigating brain function in this group at later time points would be useful in this respect.

The current epidemiological study should be considered as a pilot to further longitudinal research and requires replication using larger numbers and independent samples. Nevertheless, it suggests a relationship between MP-use and subtle EEG slowing, and between MP-use and enhanced executive function. The nature of the effect is still unclear and no conclusions can be drawn with respect to adverse health effects or whether this effect reflects an adaptive brain response. It should also be noted that the questionnaire used in the current study has not been fully validated and only gives a crude indication of MP use. Future studies should therefore incorporate more accurate and validated measures of the extent of MP use and extend the number of recording sites to include frontal areas.

REFERENCES

- Banik, S., Bandyopadhyay, S., & Ganguly, S. (2003). Bioeffects of microwave—a brief review. *Bioresource Technologies*, 87, 155–159.

- Bernardi, P., Cavagnaro, M., Pisa, S., & Piuze, E. (2000). Specific absorption rate and temperature increases in the head of a cellular-phone user. *IEEE Transactions on Microwave Theory and Techniques*, *48*, 1118–1126.
- Borbély, A. A., Huber, R. H., Graf, T., Fuchs, B., Gallmann, E., & Achermann, P. (1999). Pulsed high-frequency electromagnetic field affects human sleep and sleep electroencephalogram. *Neuroscience Letters*, *275*, 207–210.
- Clark, C. R., Paul, R. H., Williams, L. M., Arns, M., Fallahpour, K., Handmer, C., & Gordon, E. (2006). Development of ageing across the lifespan using common neuropsychological indices on an automated test battery. *Archives of Clinical Neuropsychology*.
- Costa, Jr., P. T., & McCrae, R. R. (1992). NEO PI-R: *Professional manual (Revised NEO Personality Inventory (NEO PI-R) and NEO Five-Factor Inventory (NEO-FFI))*. Odessa, FL: Psychological Assessment Resources, Inc.
- Croft, R. J., Chandler, J. S., Burgess, A. P., Barry, R. J., Williams, J. D., & Clarke, A. R. (2002). Acute mobile phone operation affects neural function in humans. *Clinical Neurophysiology*, *113*, 1623–1632.
- Dutch Health Council. (2002). *Mobiele telefoons; een gezondheidskundige analyse*. Den Haag: Dutch Health Council publicatie nr. 2002/01
- Eulitz, C., Ullsperger, P., Freude, G., & Elbert, T. (1998). Mobile phones modulate response patterns of human brain activity. *Neuroreport*, *9*, 3229–3232.
- Gordon, E. (2003). Integrative neuroscience in psychiatry: The role of a standardized database. *Australasian Psychiatry*, *11*(2), 156–163.
- Gordon, E., Cooper, N., Rennie, C., Hermens, D., & Williams, L. (2005). Integrative neuroscience: The role of a standardized database. *Clinical EEG and Neuroscience*, *36*, 64–75.
- Gratton, G., Coles, M. G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*, 468–484.
- Haarala, C., Bjornberg, L., Ek, M., Laine, M., Revonsuo, A., Koivisto, M., & Hamalainen, H. (2003). Effect of a 902 MHz electromagnetic field emitted by mobile phones on human cognitive function: A replication study. *Bioelectromagnetics*, *24*(4), 283–288.
- Huber, R., Graf, T., Cote, K. A., Wittmann, L., Gallmann, E., Matter, D., Schuderer, J., Kuster, N., Borbely, A. A., & Achermann, P. (2000). Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG. *Neuroreport*, *11*, 3321–3325.
- Huber, R., Borbely, A. A., Gottselig, J. M., Kuster, N., Landolt, H. P., Schuderer, J., Werth, E., & Achermann, P. (2002a). Electromagnetic fields and the sleep EEG: Effect of signal modulation. *European Sleep Research Society, JSR*, *11*, 106: 213.
- Huber, R., Treyer, V., Borbely, A. A., Schuderer, J., Gottselig, J. M., Landolt, H. P., Werth, E., Berthold, T., Kuster, N., Buck, A., & Achermann, P. (2002b).

- Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. *Journal of Sleep Research*, *11*, 289–295.
- IEGMP. (2000). Mobile phones and health. Report of an independent expert group on mobile phones. UK Minister of Public Health. National Radiological Protection Board, Chilton, Oxon. Available at www.iegmp.org.uk
- Koivisto, M., Revonsuo, A., Krause, C. M., Haarala, C., Sillanmäki, L., Laine, M., & Hämäläinen, H. (2000). Effects of 902 MHz electromagnetic field emitted by cellular phones on response times in humans. *Neuroreport*, *11*, 413–415.
- Koivisto, M., Krause, C. M., Revonsuo, A., Laine, M., & Hämäläinen, H. (2000). The effects of electromagnetic field emitted by GSM phones on working memory. *Neuroreport*, *11*(8), 1641–1643.
- Kramarenko, A. V., & Tan, U. (2003). Effects of high-frequency electromagnetic fields on human EEG: A brain mapping study. *International Journal of Neuroscience*, *113*, 1007–1019.
- Krause, C. M., Sillanmäki, L., Koivisto, M., Häggqvist, A., Saarela, C., Revonsuo, A., Laine, M., & Hämäläinen, H. (2000). Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. *International Journal Radiation Biology*, *76*(12), 1659–1667.
- Krause, C. M., Haarala, C., Sillanmäki, L., Koivisto, M., Alanko, K., Revonsuo, A., Laine, M., & Hämäläinen, H. (2004). Effects of electromagnetic field emitted by cellular phones on the EEG during an auditory memory task: A double blind replication study. *Bioelectromagnetics*, *25*(1), 33–40.
- Lebedeva, N. N., Sulimov, A. V., Sulimova, O. P., Korotkovskaya, T. I., & Gailus, T. (2001). Investigation of brain potentials in sleeping humans exposed to the electromagnetic field of mobile phones. *Critical Reviews in Biomedical Engineering*, *29*, 125–133.
- Lee, T. M. C., Ho, S. M. Y., Tsang, L. Y. H., Yang, S. H., Li, L. S., Chan, C. C., & Yang, S. Y. (2001). Effect on human attention of exposure to the electromagnetic field emitted by mobile phones. *Neuroreport*, *12*, 729–731.
- Lee, T. M. C., Lam, P. K., Yee, L. T. S., & Chan, C. C. H. (2003). The effect of the duration of exposure to the electromagnetic field emitted by mobile phones on human attention. *Neuroreport*, *14*, 1361–1364.
- Mann, K., & Röschke, J. (1996). Effects of high-frequency electromagnetic fields on human sleep. *Neuropsychobiology*, *33*, 41–47.
- Repacholi, M. H. (2001). Health risks from the use of mobile phones. *Toxicology Letters*, *13*, 323–331.
- Rodriguez, G., Copello, F., Vitali, P., Perego, G., & Nobili, F. (1999). EEG spectral profile to stage Alzheimer's disease. *Clinical Neurophysiology*, *110*, 1831–1837.
- Röschke, J., & Mann, M. (1997). No short-term effects of digital mobile radio telephone on the awake human electroencephalogram. *Bioelectromagnetics*, *18*, 172–176.

- Schmidtke, J. I., & Heller, W. (2004). Personality, affect and EEG: Predicting patterns of regional brain activity related to extraversion and neuroticism. *Personality and Individual Differences*, in press.
- Schulze, S., Krafczyk, S., Botzel, K., Brix, J., & Matthes, R. (1996). Pulsed microwaves modulate EEG-activity in the alpha Band. *Epilepsy by: Electroencephalography and Clinical Neurophysiology*, 99(4), 318–319.
- Stough, C., Donaldson, C., Scarlara, B., & Ciorciari, J. (2001). Psychophysiological correlates of the NEO PI-R Openness, Agreeableness and Conscientiousness: Preliminary results. *International Journal of Psychophysiology*, 41, 87–91.
- Tran, Y., Craig, A., & McIsaac, P. (2001). Extraversion-introversion and 8–13 Hz waves in frontal cortical regions. *Personality and Individual Differences*, 30, 205–215.
- Van Leeuwen, G. M. J., Lagendijk, J. J. W., van Leersum, B. J. A. M., Zwamborn, A. P. M., Hornsleth, S. N., & Kotte, A. N. T. J. (1999). Calculation of change in brain temperature due to exposure to a mobile phone. *Physical and Medical Biology*, 44, 2367–2379.
- Wagner, P., Röschke, J., Mann, K., Fell, J., Hiller, W., Frank, C., & Grözing, M. (2000). Human sleep EEG under the influence of pulsed radio frequency electromagnetic field: Results from polysomnographies using submaximal high power flux densities. *Neuropsychobiology*, 42, 207–212.
- Wainwright, P. (2000). Thermal effects of radiation from cellular telephones. *Physical Medicine Biology*, 45, 2363–2372.
- Wang, J., & Fujiwara, O. (1999). FDTD computation of temperature rise in the human head for portable telephones. *IEEE Trans Microwave Theory Tech*, 47, 1528–1534.
- Williams, L. M., Simms, E., Clark, C. R., Paul, R. H., Rowe, D. L., & Gordon, E. (2005). The test-retest reliability of a standardized neurocognitive and neurophysiological test battery. *International Journal of Neuroscience*, 115, 1605–1630.