TURUN YLIOPISTON JULKAISUJA
ANNALES UNIVERSITATIS TURKUENSIS

SARJA - SER. B OSA - TOM. 322

HUMANIORA

EFFECTS OF MOBILE PHONE ELECTROMAGNETIC FIELD: BEHAVIORAL AND NEUROPHYSIOLOGICAL MEASUREMENTS

by

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Turku 2009

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ISBN 978-951-29-4106-3 (PRINT)
ISBN 978-951-29-4107-0 (PDF)
ISSN 0082-6987
Painosalama Oy – Turku, Finland 2009

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INTRODUCTION

Mobile phone use has increased dramatically in recent years, reaching up to 4.1 billion subscribers in 2008 [ITU, 2009]. Mobile phone use in close proximity to the head has increased public concern about adverse effects of mobile phone radiation on the nervous system in the head. For the last decades, a large number of studies have investigated the possible effects of mobile phone exposure, mainly of short-term exposure to digital handset-like signals, with various methods for investigating cognition and brain functioning.

Radiofrequency (RF) electromagnetic radiation is used in mobile phones to transmit information between handsets and base stations, and the information can be transmitted in either analog or digital form. Different mobile phone systems use different signals (different frequency bands and information coding methods). The first generation (1G) of cellular mobile telecommunication systems, such as the Nordic Mobile Telephone (NMT) introduced in 1980s, used analog signals, which were usually frequency-modulated and continuous (not pulsed). The analog systems were then replaced by the digital 2G systems in 1990s, which have many technical advantages over the analog systems (e.g., multiplexing, data compression). Global system for mobile communications (GSM) is the most widely used 2G system for mobile phone communications in the world. About 3.5 billion mobile phone connections use GSM across 222 countries, which is over 80% of all the connections in the world (ca. 4.4 billion) [GSM Association, 2009].

The GSM network operates in the 900 and 1800 MHz bands in most countries. For example, GSM-900 uses a frequency of 890-915 MHz to transmit signals from a handset to a base station (uplink) and a frequency of 935-960 MHz for the other direction (downlink). Frequency-division multiple access (FDMA) allows 124 RF channels of 200 kHz wide, which can be used simultaneously. Each base station is assigned a different set of channels to serve mobile phones, avoiding interference with neighboring base stations. Time-division multiple access (TDMA) allows several users to share the same RF channel by dividing the data stream into time slots allocated to each user. The users transmit in rapid succession, one after another, using own time slots.

The GSM signal is pulse-modulated at a frequency of 217 Hz with a frame length of 4.6 ms and each frame is divided into eight slots with a pulse width of 0.577 ms, allowing eight simultaneous calls on the same channel. One slot is active in handset signals and seven in base station signals. Since the transmission power is limited to a peak power of

2 W for GSM-900 and 1 W for GSM-1800, the averaged power is 0.25 W and 0.125 W, respectively, for handset signals because of the duty cycle of 1/8.

In the GSM signals pulse-modulated at 217 Hz, every 26th pulse is idle by definition, causing a modulation component at 8 Hz ('talk' mode). In 'listen' mode, discontinuous transmission (DTX) for saving battery power produces additional pulsing at 2 Hz. In 'standby' mode when the phone is switched on without an active call, the carrier frequency pulses less periodically at below 2 Hz. Thus, the GSM signal have modulation components of 2, 8, 217, 1733 Hz, and higher harmonics, and the different spectral composition of 'talk', 'listen', and 'standby' signals affect the output power and thus the amount of radiation energy absorbed by adjacent tissue (talk > listen > standby $\approx$ 0 W/kg) [Hung et al., 2007; Hyland, 2000].

Specific absorption rate (SAR) is a measure of the rate at which RF energy is absorbed by a unit mass of tissue (W/kg) [Durney et al., 1986]. Exposure limits relevant to mobile phones are expressed in terms of the SAR averaged over a small sample volume (typically 1 or 10 g) of tissue, for instance, SAR1g < 1.6 W/kg [IEEE, 2005] and SAR10g < 2.0 W/kg [ICNIRP, 1998]. The (worst-case) spatial average SAR in the user's head would be the maximum output (2.5 W) divided by the mass of the head, but local peak values can be much higher depending on the distance to the phone and tissue type [Gandhi, 2002]. The local peak SAR that have been determined by measurements with a phantom (SAR_{1g} = 1.20 W/kg, SAR_{10g} = 0.86 W/kg) or numerical simulations (II, TABLE 1) are slightly but not much lower than the guidelines.

LITERATURE REVIEW

Subjective symptoms and EMF perception

Cross-sectional studies from various countries reported that a small but significant proportion of the population experience subjective or nonspecific symptoms associated with EMF exposure: 1.5% in Sweden [Hillert et al., 2002], 3.2% in California [Levallois et al., 2002], 5% in Switzerland [Schreier et al., 2006]. Moreover, a majority (56%) of the people with self-reported hypersensitivity reported being able to perceive EMF [Röösli et al., 2004]. Electromagnetic hypersensitivity is characterized by a variety of nonspecific symptoms (e.g., headache, dizziness, fatigue, sleep disorder) and may be recognized as functional impairment [Johansson, 2006; WHO, 2005], but is not currently an accepted diagnosis. These survey studies, based on subjective statements or observations, are inappropriate for addressing causal relationship between EMF exposure and subjective symptoms or for providing objective evidence of the ability of humans to perceive EMF.

The (self-reported) ability to perceive or sense EMF, referred to as electromagnetic sensibility, may not be a necessary condition for hypersensitivity [Leitgeb & Schröttner, 2003], and electromagnetic hypersensitivity and sensibility are even considered as two independent phenomena [Seitz et al., 2005]. Leitgeb and Schröttner [2003] analyzed the distribution of the perception threshold of a 50 Hz electric current in 708 adults and found a significant deviation (lower threshold), suggesting the existence of increased sensibility to the low frequency EMF in the general population. Mueller et al. [2002] also found a small number of subjects sensitive to 50 Hz EMF, with no difference between the two groups with and without self-reported hypersensitivity. Some other provocation studies have provided evidence against such ability to perceive low frequency EMFs, especially in self-reported hypersensitive subgroups [Lyskov et al., 2001; Reißenweber et al., 2000].

Aforementioned studies have used low frequency EMFs, but sensibility to low frequency fields does not necessarily correlate with that to RF fields used in mobile telecommunications [Leitgeb & Schröttner, 2003]. There have been only a small number of provocation studies on the perception of mobile phone EMF, providing little evidence for the ability to perceive EMFs in hypersensitive individuals. For example, Hietanen et al. [2002] reported that 20 hypersensitive subjects failed to distinguish real exposure to mobile phone radiation from sham exposure (30 min, 3-4 trials), and Raczek et al. [2000]

also reported that 16 hypersensitive subjects failed to discriminate between real exposure to mobile phone radiation and sham exposure (3 min, 21 trials). However, sample groups in previous studies were largely limited to self-reported hypersensitive subjects although the possible sensibility and hypersensitivity are not necessarily related to each other [for reviews see Rubin et al., 2005; Seitz et al., 2005]. In addition, the sample size (i.e., number of subjects and trials) was often too small to ensure statistical confidence.

Cognitive performance

The effects of mobile phone radiation on cognitive functions have been investigated in a number of studies by comparing performance measures (e.g., accuracy, speed) of various cognitive tasks under different exposure conditions. Previous studies have often used attention or working memory tasks. For instance, reaction time (RT) tasks measure subjects' RT to one single stimulus (simple RT) or several complex stimuli (choice RT). In other attention tasks, subjects respond to a target stimulus presented in a series of non-target stimuli (vigilance task), or subtract one-digit numbers from nine (subtraction task). In n-back working memory tasks, subjects were to respond to each stimulus (letter in this study) whether it appeared n trials back. Early studies often reported significant effects such as increased speed in those tasks [Preece et al., 1999; Koivisto et al., 2000a, 2000b], but these studies tested many variables obtained from a series of tasks without enough consideration for multiple comparisons. Later studies even by the same research groups have failed to replicate the previous findings despite methodological improvement.

Preece et al. [1999] reported choice RT being reduced in a dose-dependent manner (analog 1 W < digital 0.125 W < sham 0 W), but it was the only significant result ($P = 0.003$) out of 15 tested variables from ten attention and memory tasks. Subsequently, Preece et al. [2005] tested the observed dose-dependent effect in children using two digital signals of 0.25 and 0.025 W and the same attention and memory tasks slightly modified for children. They found a similar trend of better performance, most marked in reduced simple RT ($P = 0.02$), but none of the variables reached statistical significance after Bonferroni corrections (22 tests). They concluded the replication to have failed in children.

Koivisto et al. [2000a] reported reduced RT in a working memory task (3-back), and Koivisto et al. [2000b] also reported reduced RT in simple RT, subtraction, and vigilance tasks. However, simple RT ($P = 0.026$) and subtraction RT ($P = 0.044$) results did not reach statistical significance when corrected for multiple testing (14 tests). Their replication studies with improved study design (larger sample size, double-blind design,

multicenter testing, additional attention tasks) found no significant effects in either RT (attention) [Haarala et al., 2003b] or working memory [Haarala et al., 2004; Haarala et al., 2003a] tasks. They conducted further experiments in children [Haarala et al., 2005], or in adults including additional exposure conditions (CW signals, both left and right exposure) and a control group with no exposure equipment [Haarala et al., 2007]. The tasks were selected considering the facilitating effects observed in the previous studies [Koivisto et al., 2000a, 2000b] but neither of the studies found any significant effects.

The cognitive facilitating effects on attention [Koivisto et al., 2000b] and memory [Koivisto et al., 2000a] were also tested by Russo et al. [2006] and Cinel et al. [2008], respectively, using a large sample of 168 subjects for improved statistical power. Russo et al. [2006] included simple RT, subtraction, and vigilance tasks that might be sensitive to exposure [Koivisto et al., 2000b], while Cinel et al. [2008] manipulated task difficulty because the exposure might affect cognitive functions only in the high cognitive load conditions (3-back) [Koivisto et al., 2000a]. Using otherwise identical exposure setup, study design, and statistical analysis, neither of the studies found any significant effects.

Curcio et al. [2004] found significantly reduced simple and choice RT, but Curcio et al. [2008] subsequently reported no effects in the same simple RT task (choice RT task not tested) or in a sequential finger tapping task. Regel et al. [2007a, 2007b] found no facilitating effects in simple and choice RT tasks but only inconsistent results in n-back memory tasks: improved performance (reduced RT, enhanced accuracy) in Regel et al. [2007a] but then the opposite results (increased RT with increasing SAR levels) in Regel et al. [2007b]. Keetley et al. [2006] reported impaired simple and choice RT, rejecting the hypothesis of facilitating effects, but improved RT in a trail-making task. Furthermore, these results ($P = 0.005$-0.043) were not adjusted for multiple testing (18 tests).

Besset et al. [2005] and Fritzer et al. [2007] examined long-term cumulative effects of a 2 h daily exposure for four weeks and of exposure during a whole night sleep of about 8 h for six nights, respectively, finding no significant effects on attention, memory, or executive functions. Aside from the frequently investigated attention and memory functions, Maier et al. [2004] reported increased auditory temporal-order thresholds, the minimum time to discriminate two successive tone presented to each ear, while no effects were found in visual luminance-discrimination thresholds [Irlenbusch et al., 2007] and critical flicker fusion thresholds [Wilén et al., 2006]. No effects of 2G digital signals were found in visuo-motor preparation [Terao et al., 2006], and saccades [Terao et al., 2007]. Finally, 3G digital signals were also found not to affect attention [Regel et

al., 2006; Unterlechner et al., 2008], memory [Regel et al., 2006], or visual perception [Schmid et al., 2005].

Some studies had problems in data analysis and interpretation. For instance, Eliyahu et al. [2006] and Luria et al. [2009] arbitrarily combined the data from different exposure conditions (right, sham) in order to yield significant results (left) on laterality. Smythe and Costall [2003] excluded a certain condition (no phone) because the initial analysis comparing all conditions (on, off, no phone) revealed no significant results on short-term and long-term memory functions. Wiholm et al. [2009] reported that the performance of a virtual navigation task was improved (distance traveled was decreased) in a hypersensitive group after real exposure, but the performance of the hypersensitive group was actually worsened after sham exposure, with no differences between the hypersensitive (real) and control (real, sham) groups. This suggests that the observed effect might be due to chance.

In sum, the issue of multiple comparisons was not taken into account in the earlier behavioral studies, which reported a few significant results in a number of tests. Thus, the positive findings may be explained by chance. Later more elaborate studies could not replicate these results. Considering recent findings of null effects, mobile phone radiation does not seem to have measurable effects on cognitive functions assessed with behavioral measures.

Cochlear and brainstem auditory processing

Auditory organs such as the ear absorb most of the radiation energy from the mobile phone [Parazzini et al., 2007b], prompting investigations on the auditory function in humans with audiometric tests used for diagnosis of hearing loss or ear diseases. Previous studies usually used pure tone audiometry (PTA), otoacoustic emission (OAE), or auditory brainstem response (ABR) [Parazzini et al., 2007a]. Compared with subjective audiometry such as PTA, the OAE and ABR provide more sensitive and reliable methods for detecting subtle disturbances of hearing function due to EMF exposure, for instance.

OAE

The OAE is a natural sound signal generated from the cochlea due to the motility of the outer hair cells related to sound amplification [Kemp, 1978, 2002]. The OAE is objectively measurable in the ear canal and provides a very sensitive index of cochlear damage by monitoring the status of the outer hair cells. Mild changes in the cochlear function that are not revealed by subjective audiometric tests such as PTA can cause

obvious changes in the OAE [Kemp, 2002]. Evoked OAE includes transiently evoked OAE (TEOAE) elicited by click stimuli and distortion product OAE (DPOAE) elicited by a pair of pure tones with particular intensity and frequency ratio.

Previous mobile phone studies compared either TEOAE [Bamiou et al., 2008; Mora et al., 2006; Paglialonga et al., 2007; Uloziene et al., 2005], DPOAE [Parazzini et al., 2005], or both [Ozturan et al., 2002] measured before and after short-term exposure (10 or 30 min) to the GSM signal. However, none of them found any effects of the exposure, even using sophisticated data processing for increasing the sensitivity to detect small changes in hearing function due to exposure [Paglialonga et al., 2007; Parazzini et al., 2005]. As for the vestibular part of the inner ear, Bamiou et al. [2008] and Pau et al. [2005] found no evidence of nystagmus due to short-term exposure as measured with video-oculography (VOG).

ABR

The ABR is an electrical response evoked from the brainstem by a sound such as a rarefaction click [Jewett et al., 1970; Jewett and Williston, 1971]. The sound signal travels along the auditory pathway producing small deflections of the ABR within 10 ms following stimulus onset. The ABR involves auditory nerve and nuclei located in the brainstem, providing information about cochlear and retrocochlear auditory functions and hearing sensitivity [Henry, 1979]. Wave I originates from the acoustic nerve (8^{th} cranial nerve), wave III from the superior olivary complex (lower pons), and wave V from the inferior colliculus (midbrain). Kellényi et al. [1999] first reported that the latency of wave V was delayed by 0.207 ms after 15 min exposure to a GSM signal.

Thereafter, several studies were conducted to determine the effects of short-term exposure (10 or 30 min) to mobile phone EMF on the ABR [Arai et al., 2003; Bąk et al., 2003; Mora et al., 2006; Oysu et al., 2005; Sievert et al., 2005; Stefanics et al., 2007], none of them finding significant effects on any ABR variables. Even the same group [Stefanics et al., 2007] failed to replicate their preliminary findings [Kellényi et al., 1999] in experiments with several improvements compared to the first study (sample size, stimulus type, double-blind, counterbalancing). Arai et al. [2003] measured the ABR and its recovery function, as well as middle latency responses (MLR) with negative (Na) and positive (Pa, Pb) waves at 10-75 ms latency. The MLR originates from thalamo-cortical projections and temporal auditory cortex [Picton et al., 1974; Picton and Hillyard, 1974], in addition to subcortical generators, but they found no significant effects. Finally, Oktay and Dasdag [2006] studied long-term effects of mobile phone use in heavy, moderate, and non-users but found no effects on the ABR.

In sum, previous OAE and ABR studies were quite consistent in experimental setup and provided consistent results of no effects. However, only a few ABR studies applied concurrent exposure with the radiation source being placed apart from the ear [Sievert et al., 2005] or on the head over the temporo-occipital region [Bąk et al., 2003]. The OAE was not measured during exposure at all. This is an important issue because the effects of mobile phone radiation with the weak transmission power can be transient.

Brain activity during cognitive processing

Electroencephalogram (EEG) is electrical activity within the brain recorded with electrodes attached to the scalp [Berger, 1929]. The EEG signal is a mixture of simultaneous oscillations traditionally subdivided into EEG frequency bands such as delta (< 4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (> 30 Hz). As derivatives of EEG techniques, event-related desynchronization and synchronization (ERD/ERS) refer to the relative EEG spectral power decrease and increase, respectively, in defined frequency bands occurring in relation to an event [Pfurtscheller 1992]. In the time domain, evoked (EP) and event-related potentials (ERP) refer to the averaged brain responses time-locked to the presentation of external stimuli or more complex cognitive processing of internal/external stimuli, respectively. Positive or negative deflections are measured on a millisecond time scale, for example, N100 denoting a negative deflection at about 100 ms latency. These techniques have been extensively used in studying human cognitive functions.

Resting EEG

Despite the differences in study design, previous studies on resting EEG have rather consistently reported enhanced alpha activity (8-12 Hz) due to mobile phone exposure [Croft et al., 2002; Curcio et al., 2005; Regel et al., 2007a; Reiser et al., 1995], and Croft et al. [2008] confirmed this alpha power enhancement by using a large sample size (N = 120 subjects). In addition, Vecchio et al. [2007] reported modulated interhemispheric EEG spectral coherence also in the alpha band: increased temporal coherence at 8-10 Hz and decreased frontal coherence at 8-10 and 10-12 Hz. Thus, mobile phone radiation may have affected underlying thalamic mechanisms of alpha rhythm generation [Hughes and Crunelli, 2005], which is prominent during relaxed wakefulness (eyes closed). Some studies reported significant effects also in the delta [Croft et al., 2002] and beta [Reiser et al., 1995] bands.

Some other studies have reported no significant effects of mobile phone exposure on resting EEG [Hietanen et al., 2000; Kleinlogel et al., 2008a; Perentos et al., 2007; Röschke

and Mann, 1997]. Notably, Hietanen et al. [2000] compared five analog or digital phones operating at 900 or 1800 MHz and found increased absolute power in the delta band (1.5-3.5 Hz) for an analog NMT-900 phone at an alpha level of 0.01 ($P = 0.004$). However, they concluded to have found no significant effects because the observed effect could be due to multiple comparisons (36 variables, 180 t-tests). Otherwise, a similar difference should have been observed in the relative power, which was not the case. Analog signals induced no effect on the resting EEG [Regel et al., 2007a; Perentos et al., 2007].

Sleep EEG

A series of studies on sleep EEG [Borbély et al., 1999; Huber et al., 2000, 2002] found enhanced EEG spectral power in subjects exposed to mobile phone radiation in the alpha band of sleep EEG and in the adjacent sleep spindles range (12-16 Hz) during the initial part of non-REM (rapid eye movement) sleep. Loughran et al. [2005] attempted to replicate these findings [Huber et al., 2000, 2002] by recording EEG for the first 30 min of the initial non-REM sleep after 30 min exposure prior to night sleep. The results showed similar spectral power enhancement in the slow sleep spindle range. Regal et al. [2007b] found dose-dependent increase in the sleep spindle range in non-REM sleep using five times lower (0.2 W/kg) and higher (5 W/kg) than in their earlier experiments (SAR10g = 1 W/kg) [Borbély et al., 1999; Huber et al., 2000, 2002], further corroborating the earlier findings.

In contrast, a series of studies reported null findings [Mann and Röschke, 1996; Wagner et al., 1998, 2000]. Mann and Röschke [1996] first reported sleep-inducing effect (reduced sleep onset latency), suppressed REM sleep (prolonged latency, reduced duration), and enhanced alpha power during RAM sleep. However, Wagner et al. [1998] with improved dosimetry found no effects, attributing the discrepancy to lower field intensity (0.2 W/m^2 < 0.5 W/m^2) or different antenna and signal type. In further studies, Wagner et al. [2000] employed considerably higher power density (50 W/m^2) but still found no effects, rejecting the possibility of a dose-dependent effect. Finally, Fritzer et al. [2007] found no cumulative effects of six-night consecutive exposure on sleep EEG.

In sum, previous resting and sleep EEG studies have provided conflicting results (i.e., enhance alpha activity vs. null effects). Moreover, it is difficult to compare the findings to draw any conclusions because of huge discrepancies in the experimental setup, especially in the exposure characteristics. For instance, the same series of studies used a intermittent base station signal (15 min on, 15 min off) for 8 h night sleep [Borbély et al., 1999], a base station signal for 30 min prior to 3 h daytime sleep [Huber et al., 2000], or a handset signal for 30 min prior to 8 h night sleep including an analog signal [Huber et

al., 2002]. Even replication studies sometimes differed from the studies to be replicated in experimental setup (e.g., Wagner et al. [1998, 2000]).

Low frequency modulation components may be a reason for the inconsistency. The 450 MHz microwave radiation has been shown to affect the EEG differently at different modulation frequencies [Hinrikus et al., 2007, 2008; Bachmann et al., 2005, 2006]. Regarding mobile phone radiation, Hung et al., [2007] compared the three different modes (talk, listen, standby) of GSM signals with different spectral composition and thus different output power and SAR, and reported delayed sleep latency after talk mode exposure. Further investigation is thus needed to determine the critical modulation frequencies for human brain activity. The inconsistency may also be attributed to the difference between the base station and the handset signals. The latter, for instance, provides higher spectral power of the 2 and 8 Hz modulation components and four times higher peak SAR, while maintaining the same time-averaged SAR [Huber et al., 2002].

ERD/ERS

Some studies analyzed the ERP reflecting auditory discrimination process in an auditory oddball task in the frequency domain. Eulitz et al. [1998] reported altered P300 responses to the target stimuli in the 18.75-31.25 Hz range, mainly in the ipsilateral hemisphere. Croft et al. [2002] also found altered neural activities (ERD/ERS) in various frequency bands, but Stefanics et al. [2008] found no effect on early gamma (30-50 Hz) power and coherence in an auditory oddball paradigm. Papageorgiou et al. [2004] found gender-related effects on auditory working memory using a digit span forward/backward test: EEG energy was larger in males than in females at baseline, while it decreased in males and increased in females under exposure. However, this study tested separately for each electrode and frequency band without corrections for multiple comparisons.

Krause et al. [2000a, 2000b, 2004, 2006, 2007] extensively investigated the effects of a GSM-900 handset signal on memory functions using ERD/ERS. They first examined auditory memory encoding and retrieval [Krause et al., 2000a] and visual working memory (n-back) [Krause et al., 2000b], both using right side exposure and a single-blind design. The auditory memory results showed increased spectral power in 8-10 Hz during retrieval and altered ERD/ERS as a function of time and phase (encoding vs. retrieval) in all frequency bands analyzed (4-6, 6-8, 8-10, 10-12 Hz). The results on visual working memory showed altered ERD/ERS in 6-8 and 8-10 Hz as a function of memory load (0-2 items) and stimulus type (target, non-target).

They replicated the auditory memory encoding and retrieval study in adults [Krause et al., 2004] and children [Krause et al., 2006] using the opposite left side exposure in

a double-blind design but the results were inconsistent. In adults, they found decreased power in 4-6 Hz and altered ERD/ERS only in the 6-8 Hz band during both encoding and retrieval. They also found an increased error rate not observed in the previous study. In children, ERD/ERS was altered in 4-8 and around 15 Hz. Finally, Krause et al. [2007] used both tasks comparing the effects of left and right side exposures, and analog and digital signals, but only found modest effects in the alpha band.

In sum, the ERD/ERS results were very complex, often described simply with 'altered', and completely inconsistent, putting the general repeatability of the method itself into doubt. In addition, the statistically significant results mostly came from higher order interactions rather than main effects in the analysis of variance (ANOVA), making it difficult to interpret the results simply based on exposure conditions.

EP/ERP

Auditory organs as well as the temporal cortex responsible for cortical auditory processing are in close proximity to the mobile phone radiation source, so that previous studies often investigated auditory EP or ERP. Maby et al. [2004, 2006] reported reduced amplitude and latency of an auditory EP (N100) in nine adults. Similarly, Hamblin et al. [2004] reported reduced N100 amplitude and latency and increased P300 latency in 12 adults during an auditory oddball task. However, Hamblin et al. [2006] found no effects in either auditory or visual oddball tasks using a larger sample size of 120 subjects and a double-blind design. More recent studies also found no effects of mobile phone radiation on auditory EP (N100) [Kleinlogel et al., 2008b] or ERPs (e.g., P300) [Kleinlogel et al., 2008b; Stefanics et al., 2008] elicited during an auditory oddball task.

Papageorgiou et al. [2006] examined auditory P50 component reflecting preattentive information processing in working memory operations (digit span forward/backward), reporting increased amplitude for the low tone signal (forward) and decreased amplitude for the high tone signal (backward). However, since the P50 amplitude was compared separately for each electrode (15) and tone (2), the significant results might be due to statistical chance (30 tests, alpha = 0.05). Finally, Kleinlogel et al. [2008b] and Yuasa et al. [2006] reported no effects of digital signals on the visual EP (P100) and the somatosensory EP and its recovery function, respectively.

On the other hand, Freude et al. [1998, 2000] reported a rather consistent effect on the preparatory slow brain potential (SP). Freude et al. [1998] investigated the slow potential in two tasks of different cognitive demand, a simple finger movement task and a complex visual monitoring task. The amplitude of the slow potential was reduced in the high-demanding visual monitoring task, interestingly in the contralateral hemisphere.

Freude et al. [2000] replicated this study by including an additional (low-demanding) two-stimulus task to elicit contingent negative variation (CNV). They found reduced amplitude only in the same visual monitoring task over similar regions, confirming selective effect of exposure on the slow potential depending on the task demand.

In sum, EP/ERP studies involved similar issues of multiple comparisons (and possibility of false positive findings) and replication as in the behavioral studies. In this respect, Freude et al. [1998, 2000] (N = 16 subjects) should be replicated using a larger sample. However, the majority of studies have found no effects of mobile phone radiation on cognitive functions reflected in EP/ERP responses.

AIMS

Previous behavioral and EP/ERP studies have not provided convincing evidence for a connection between mobile phone radiation and cognitive functions. The ERD/ERS studies did not provide reliable results probably because the cortical electric responses elicited during complex cognitive performance are too sensitive to various factors. Mobile phone radiation can exert influence on, for instance, sensation without necessarily inducing any measurable changes in cognitive functions. In the previous studies on RF EMF perception, the sample size was usually too small and sample groups were limited to self-reported hypersensitive individuals often claiming their ability to perceive EMF. Thus, it is an open question whether ordinary people without subjective hypersensitivity can perceive RF EMF.

The possible effects of mobile phone radiation on the auditory system can be rather transient because of the weak transmission power. However, the previous studies rarely measured auditory responses during simultaneous exposure to the mobile phone placed on the same position as in ordinary mobile phone use. Objective audiometric tests such as OAE and ABR can provide very sensitive and reliable methods for detecting subtle changes in auditory function due to EMF exposure. Especially the ABR provides information about auditory processing at the peripheral (cochlea, acoustic nerve) as well as more central (brainstem) nervous system levels.

As for cortical auditory processing, the mismatch negativity (MMN) provides a sensitive measure for auditory discrimination processing regardless of attention and other contaminating factors that may have caused inconsistency in the literature. The MMN is elicited by infrequent deviant stimuli in a homogeneous stimulus sequence regardless of attention or behavioral tasks [Näätänen et al., 1978]. The MMN reflects preattentive automatic change detection process based on the memory trace of the repetitive standard stimulus and the subsequent automatic orienting response [Näätänen, 1990]. The supratemporal auditory cortices and the right prefrontal cortex are involved in the MMN generation for change detection and attention switch, respectively [Opitz et al., 2002; Rinne et al., 2000].

Despite the increased use of mobile phones by children [Schüz, 2005] and the fact that the SAR of the head can be higher in children than in adults [Christ and Kuster, 2005], only a few studies have been conducted in children in the literature as already described [Haarala et al., 2005; Krause et al., 2006; Preece et al., 2005].

The research questions of the present series of studies can be summarized as follows:

I. **Can we subjectively detect RF EMF? –** Perception of mobile phone EMF in a large sample of subjects recruited from the average general population in a comprehensive provocation test with a large number of trials

II. **Does RF EMF affect cochlea and brainstem auditory pathways?** – Effects of concurrent mobile phone exposure on the cochlear and brainstem auditory processing reflected in the ABR

III. **Does RF EMF affect cortical auditory system in adults?** – Effects of short-term mobile phone exposure on the cortical auditory discrimination processing reflected in the MMN in young adults

IV. **Does RF EMF affect cortical auditory system in children?** – Effects of short-term mobile phone exposure on the cortical auditory discrimination processing reflected in the MMN in children, who could be more vulnerable to the possible effects of mobile phone exposure

METHODS

Exposure setup

In all studies presented here, a generator-amplifier setup was set to produce an EMF similar to that emitted by an ordinary GSM mobile phone: 902.4 MHz EMF with the mean power of 0.25 W pulsed at a frequency of 217 Hz with a pulse width of 0.58 μs. A GSM phone (Nokia 6310i, Nokia, Helsinki, Finland) was modified with its loudspeaker and buzzer removed. The remaining antenna was connected via a RF amplifier (Mini circuits LZY-2) to a vector signal generator (Rohde and Schwarz SMIQ 06B, Munich, Germany) with a 10 m cable. The output power from the generator-amplifier setup was regularly measured with a RF power meter (Hewlett-Packard 437B, Palo Alto, CA, USA). This exposure setup provided constant and reliable RF signals throughout the experiments. The phone was placed on the ear in the same position as during ordinary phone conversations.

The (local peak) SAR was measured before (SAR_{1g} = 1.20 W/kg, SAR_{10g} = 0.86 W/kg) and after (SAR_{1g} = 1.14 W/kg, SAR_{10g} = 0.82 W/kg) removing the loudspeaker and buzzer with Dosimetric Assessment System 4 (DASY4, Schmid and Partner Engineering AG, Zurich, Switzerland). Measurements were conducted according to the standard IEC 62209-1 [IEC, 2005] with a Standard Anthropomorphic Model (SAM) phantom filled with head tissue simulating liquid (HSL 900, conductivity $\sigma = 0.969$ S/m, relative permittivity $\varepsilon_r = 40.14$, density $\rho = 1000$ kg/m^3) at Nokia Research Center, Helsinki, Finland. The phone was in the left cheek position and the SAR peaked near the position of the removed loudspeaker on the ear (see Fig. 1 and TABLE 1 in Study II for SAR distribution and specific SAR values of selected organs, respectively).

EMF perception

Procedure

Eighty-four healthy young adults aged 24.4 ± 5.7 years (57 females) were recruited through an advertisement announcing a monetary prize (50 euro) for good performance (correct response rate ≥ 75%, N = 600 trials). Participants performed two forced-choice tasks, on/off task ("Was the field on?") and change task ("Did the field change?"), each including three different conditions of 100 trials. The on/off task included one genuine on/off condition ($P_{on} = P_{off} = 0.5$) and two sham conditions with the EMF always on (P_{on}

= 1) or off (P_{off} = 1). The change task included one change condition ($P_{on\rightarrow off}$ = $P_{off\rightarrow on}$ = 0.5) and two constant conditions with no changes, that is, with the EMF always on ($P_{on\rightarrow on}$ = 1) or off ($P_{off\rightarrow off}$ = 1). The order of the tasks and the conditions within each task was counterbalanced and the 100 trials were randomized in the genuine on/off and the change conditions.

Participants performed the tasks sitting 1.5 m away from a computer monitor in a soundproof room. A gray circle (20 cm in diameter) on the monitor screen signalled trial onset by turning to red. A question box containing yes/no buttons appeared 5 s after trial onset. As soon as participants responded to the question with a mouse, the circle turned back to gray to signal the end of the trial. The next trial began after 1 s pause. In the change condition, EMF status was changed 2.5 s after the trial onset. Once the order of tasks and conditions set by the experimenter, the computer operated the signal generator and randomized the trials, thus the experiment being in effect double-blinded.

If participants reported either ear to be more sensitive to EMF, the phone was placed on that ear. Otherwise, the phone was placed on the ear usually used for mobile phone use and, if this was not specified, handedness was used as the final criterion. Accordingly, 17 participants had the phone on the left ear and 67 on the right. Because ordinary GSM mobile phones make a small noise when the EMF is on, earplug-shaped earphones were inserted into both ears to deliver masking white noise (50 dB).

Data analysis

For the genuine on/off condition, one-sample t-tests (two-tailed) were conducted to determine whether the performance (correct response rate, %) different from the 50% chance level and to compare the signal detection theory measures, d′ (sensitivity) and c (response bias) [Stanislaw & Todorov, 1999], with zero. For the whole data, four-way repeated-measures ANOVA with gender (2 levels: female, male), sensibility (2 levels: with, without), condition (6 levels: three conditions of each task), and interval (10 levels: intervals of 10 trials within each condition) factors were conducted. The interval factor was included in order to analyze the data as a function of time.

ABR

Procedure

Seventeen healthy young adults aged 25.9 ± 4.3 years (11 females, 2 left-handed) participated in this study. The ABR recording was carried out according to the routine clinical procedure at the department of clinical neurophysiology, Turku University

Hospital. Participant were lying on a reclining chair in a soundproof laboratory, being relaxed with the eyes closed. A nurse inserted tubal insert phone electrodes (TIPtrode, Nicolet Biomedical Instruments, Madison, WI, USA) and attached three Ag-AgCl electrodes, a ground at the midline and two reference for each side at the Fp1′ and Fp2′ positions according to the international 10/20 system of electrode placement [Jasper, 1958]. Impedance was kept under 5.0 kΩ.

The ABR was recorded with an eight-channel Nicolet Viking IV device (Nicolet Biomedical Instruments, Madison, WI, USA) after measuring auditory thresholds to click stimuli. The TIPtrode delivered auditory stimuli as well as recorded the ABR from the outer ear canal. Auditory stimuli were conducted to the ears through thin flexible silicon tubes and polyurethane foam eartips wrapped in thin gold foil. The ABR was elicited by a rarefaction click stimulus of 85 dB nHL intensity and 100 μs duration given at a rate of 10.3 Hz, while masking white noise of 45 dB nHL was delivered to the contralateral ear. The responses were amplified with the high and low pass filters set at 100 Hz and 3 kHz, respectively. The ABR was recorded at least twice to ascertain reproducibility.

Both ears were stimulated one at a time, first the right then the left, under three different conditions: without a mobile phone (baseline) and then with the phone placed on the stimulated ear, either emitting EMF (EMF-on) or not (EMF-off). The recordings always began with the baseline condition and the order of the following two conditions was counterbalanced. The ABR was always checked for EMF-induced artifacts (regular rectangular-shaped pulses) during recordings. Each ABR recording took less than 5 min and the whole experiment took 1 h.

Data analysis

According to clinical routine, the main ABR waves I, III, and V were identified and marked manually on a computer by a nurse and the results were visually analyzed by a clinical neurophysiologist. The absolute latencies of waves I, III, and V, and their interwave intervals (I-III, III-V, I-V) were measured. The amplitudes of waves I and V were measured from the negative peak to the following trough (I′, V′) and amplitude ratios (I/V) were calculated. Repeated-measures two-way ANOVA with condition (3 levels: baseline, EMF-on, EMF-off) and side (2 levels: left, right) factors were conducted on each ABR variable (amplitude, latency, interwave interval).

ERP

Procedure

Seventeen healthy young adults aged 23.1 ± 4.5 years (12 females, 2 left-handed) and 17 healthy children aged 11-12 years (13 females, all right-handed) participated in the two studies III and IV, respectively. During experiments, participants were sitting in an armchair in a soundproof room watching a movie without sound. Earplug-shaped earphones were inserted into both ears and the phone attached to a headset was placed on the ear. Participants were instructed not to pay attention to the auditory stimuli, which were conducted to the ears through thin flexible silicon tubes and foam eartips using STIM 10 Ω insert earphone kits (NeuroScan, Herndon, VA, USA).

The EEG was recorded in three blocks with the phone on one ear, one block with EMF off and two with it on, and then the three-block recording continued with the phone on the other ear. The order of the exposed ear and the three blocks of EMF on or off was counterbalanced. One recording block lasted for 6 min and the whole experimental session took 1 h including preparation for EEG recordings. The experiment was conduced in a single-blind manner but since the experimenter visited only once in order to change the phone to the other side, not between single blocks with EMF on or off, the participant had no clue when it would be on or off.

The standard stimulus was a harmonic tone composed of three sinusoidal tones or harmonic partials of 523, 1046, and 1569 Hz corresponding to c^2 on the Western musical scale. The second and third partials were lower than the first in intensity by 3 and 6 dB, respectively, and the intensity was 60 dB and the duration was 75 ms including 5 ms rise and fall times (linear ramp). The deviant stimulus differed from the standard in one sound feature only: duration (50 ms decrease), intensity (10 dB decrease), frequency (9.6% increase), or by having a gap (10 ms, 5 ms fall and rise times) in the middle of the tone.

The multi-feature paradigm (Optimum-1) [Näätänen et al., 2004] was used to present the sounds, in which every other sound of the stimulus sequence (N = 840 in each block) was the standard stimulus (P = 0.5, n = 420) and every other sound was one of the four deviants (P = 0.125 for each deviant type, n = 420 = 105 × 4 types). The stimuli were binaurally presented in a pseudorandom order so that two successive deviants were never of the same type. The stimulus-onset-asynchrony (SOA, time from the onset of the previous sound to the onset of the next sound) was 425 ms and the exact duration of the auditory stimulation was 5 min 57 s (840 stimuli × 0.425 s = 357 s) for each recording block.

The EEG was recorded from 11 Ag/AgCl electrodes (F3, F4, C3, Cz, C4, P3, P4, LM, RM, VEOG, HEOG) [Jasper, 1958] with a common reference at the nose. The vertical and horizontal electro-oculogram (EOG) were recorded from the electrodes below the left eye and on the outer canthus of the right eye. Impedance was checked to be below 5 kΩ in all electrodes prior to the recordings. Continuous EEG sampled at 500 Hz was filtered offline (bandpass 1-30 Hz) and cut into epochs of 600 ms including prestimulus baseline of 100 ms. The epochs were averaged separately for the standard (mean ± SD = 522 ± 88 sweeps) and the four deviants types (131 ± 22 sweeps). Baseline correction was performed using a time window of -100 to 0 ms. Epochs including EEG or EOG voltage exceeding ±75 μV were omitted from the averaging. Since the stimulus presentation always began with five consecutive standards, the epochs for the first five standards were also omitted from the averaging. The averaged response to the standard was subtracted from that to each deviant in order to delineate the MMN (and P3a in children), resulting in four different waveforms, one for each deviant type. The P3a is elicited by deviant or novel sounds and reflects involuntary attention switching to the distracting stimuli [Escera et al., 2000].

In addition, the P1 and N2 responses to the standard sounds were also examined in children because the P1 and N2 reflect cortical sound encoding processing and dominate late-latency auditory ERP in childhood [Čeponienė et al., 2002]. The P1 is predominant at early age (1-4 years) and the N2 becomes robust at 3-6 years and then dominates until adolescence.

Data analysis in adults

The MMN peaks were identified at the time window of 100-250 ms in the grand mean waveforms at the F3 and F4 for each deviant and condition. The F3 and F4 channels placed at the left and right frontal areas, respectively, were chosen for analysis because the MMN is largest at the frontal scalp area [Alho, 1995]. The peak amplitudes and latencies were measured at the same time window of 100-250 ms and the mean amplitudes were calculated at a 40 ms period centered at the peak latencies of the corresponding grand mean responses.

One-sample t-tests were conducted to determine whether the mean amplitudes were significantly different from (i.e., more negative than) zero. Repeated-measures three-way ANOVA with site (2 levels: F3, F4), condition (3 levels: off, on-left, on-right), and deviant (4 levels: duration, intensity, frequency, gap) factors were conducted on the MMN variables (mean amplitude, peak amplitude, peak latency).

In addition, because of the possible effects of exposure side (e.g., attenuation in the hemisphere contralateral to the position of the phone), repeated-measures three-way ANOVA with site (2 levels: F3, F4), side (3 levels: sham, F3-off, F4-off; ipsilateral, F3-on-left, F4-on-right; contralateral, F3-on-right, F4-on-left), and deviant (4 levels: duration, intensity, frequency, gap) factors were conducted.

Data analysis in children

The P1 and N2 peaks were identified at the time windows of 30-150 and 150-300 ms, respectively, in the grand mean waveforms elicited by the standard stimuli at the Cz for each condition. The peak latencies were measured and the mean amplitudes were calculated at a 20 ms period centered at the peak latencies of the corresponding grand mean responses (P1: 70-90 ms, N2: 220-240 ms).

The MMN and P3a responses were delineated by subtracting the response to the standard sounds from that to each of the four deviant sounds separately. The MMN and P3a peaks were identified at the time windows of 100-280 and 200-400 ms, respectively, in the grand mean waveforms for each deviant and condition. The F3 and F4 channels were chosen for the MMN and the Cz channel for the P3a. The peak latencies were measured and the mean amplitudes were calculated at a 40 ms time window centered at the peak latencies of the corresponding grand mean responses.

One-sample t-tests (one-tailed) were conducted for each ERP to determine whether the responses were significant, that is, the mean amplitudes were significantly different from zero. Repeated-measures three-way ANOVA with condition (3 levels: off, on-left, on-right), deviant (4 levels: duration, intensity, frequency, gap), and site (2 levels: F3, F4) factors were conducted on the MMN variables (mean amplitude, peak latency). Repeated-measures two-way ANOVA with condition (3 levels: off, on-left, on-right) and deviant (4 levels: duration, intensity, frequency, gap) factors were conducted on the P3a variables. Repeated-measures one-way ANOVA were conducted on the P1 and N2 variables to compare the three different conditions.

RESULTS

All data were tested for a normal distribution (one-sample Kolmogorov-Smirnov, two-tailed). In ANOVA, Greenhouse-Geisser corrections were made when the sphericity assumption was violated [Geisser and Greenhouse, 1958; Greenhouse and Geisser, 1959] and pairwise comparisons were conducted using Bonferroni corrections.

EMF perception

None of the participant won the prize (criterion: correct response rate ≥ 75%, N = 600 trials). The performance in the genuine on/off condition of the on/off task was no better than expected by chance (50.84%, n = 100 trials). The correct response rate was around 50% throughout the genuine on/off condition (I, Fig. 2), while it was lower or higher than 50% when EMF was always on or always off, respectively. In the change task, the correct response rate was much lower in the change condition where the correct response was always "Yes", while it was much higher in the constant conditions where the correct response was always "No". This shows a response bias toward "No" and such a response tendency was stronger in the change task. Accordingly, signal detection theory measures from the genuine on/off condition indicated poor sensitivity ($d' = 0.061$) and a response bias toward the no response ($c = 0.251$), which was stronger in the change task.

The ANOVA revealed a significant main effect of condition due to response bias ($F_{2.156,168.199} = 10.990$, $P<0.0005$) but no main effects of gender, sensibility, and interval, or interactions. Two subjects with no self-reported sensibility showed extraordinary performance in the genuine on/off condition with correct response rates of 97% (binomial $P = 1.28 \times 10^{-25}$) and 94% (binomial $P = 9.40 \times 10^{-22}$). These two subjects were retested a month later in six blocks of the genuine on/off condition only but they failed to replicate their initial performance.

ABR

The main effect of condition was not significant except for the wave I latency ($F_{2,32} = 7.392$, $P = 0.002$). The mean latency of wave I was slightly longer in the EMF-on (L: 2.35 ms, R: 2.37 ms) and EMF-off (L: 2.35 ms, R: 2.37 ms) conditions than in the baseline (L: 2.33 ms, R: 2.35 ms), with no significant difference between the two EMF conditions. Therefore, the small prolongation of the wave I latency was not due to the exposure but to the presence of the mobile phone on the outer ear, which might have changed the air conductance of the click stimulus by slightly pressing the silicon tube. It could also be due to the manual peak identification or a type I error. The main effect

of side and interactions were not significant for any ABR parameters at an alpha level of 0.05.

ERP

All deviants elicit significant MMN responses except for a few cases of the intensity deviant in both adults (III, TABLE 1) and children (IV, TABLE 2). Accordingly, the main effect of deviant was significant for the mean amplitudes (adults: $F_{3,48} = 11.637$, $P < 0.0005$; children: $F_{3,48} = 8.021$, $P < 0.0005$) and the duration deviant elicited largest responses. No significant main effects of condition or site, or interactions were found in either of the studies. In adults, the main effect of side was slightly significant for the peak amplitude ($F_{1.046,16.741} = 5.124$, $P = 0.045$) but pairwise comparisons revealed no significant differences between conditions. For the peak latencies, only the main effect of deviant was found in adults ($F_{1.954,31.260} = 5.124$; $P = 0.012$).

In children, all deviants elicited small but significant P3a responses in children except for a few cases of the intensity and frequency deviants (IV, TABLE 3). Accordingly, the main effect of deviant was significant for the mean amplitudes ($F_{2.198,35.172} = 12.378$, $P < 0.0005$) and the duration deviant elicited largest responses. The main effect of condition and interactions were not significant. The ANOVA revealed slightly significant main effects of deviant ($F_{1.797,28.756} = 3.575$, $P = 0.045$) and condition ($F_{2,32} = 3.321$, $P = 0.049$) on the P3a latency but pairwise comparisons revealed no significant differences between conditions. These significant main effects were rejected after Bonferroni corrections (6 ANOVAs, alpha = 0.0083).

The N2 responses to the standard stimuli were significant in all three conditions (IV, TABLE 1), while the P1 was significant only in one condition (on-left). No significant differences were found among conditions on any of the P1 and N2 variables.

DISCUSSION

The overall performance on the subjective perception of mobile phone EMF in a large sample of general population was no better than expected by chance. An important finding was that extraordinary performance with extremely low probability could occur even twice in a sample of only 84 subjects. Such performance has not been reported even in those who strongly claimed to be able to perceive EMF. The two subjects did not know how they did it and failed in replication. This finding emphasizes the importance of replication in the EMF studies in general [also see Rubin et al., 2005].

As for response bias, people tend to make a choice in a rather balanced way in an uncertain but neutral situation. In this study, the overall response bias was towards the no response probably because they continued to perceive no changes. In contrast, those who reported themselves as being able to perceive EMF frequently made false alarms in the sham exposure condition [also see Frick et al., 2005] and a similar tendency towards the yes response was observed across conditions in this study. Since the subject's response can be affected by various factors such as a priori knowledge of the experimental design, provocation studies should employ study design and analysis that are not vulnerable to possible response bias.

The ABR results showed no measurable effects of mobile phone radiation on the transmission of sensory stimuli from the cochlea up to the midbrain along the auditory nerve and brainstem auditory pathways. In the ERP results, the duration, gap, and frequency deviants always elicited strong MMN in both adults and children with the duration deviant eliciting the largest response. The physical difference between the standard and the intensity deviant probably was too small to elicit reliable MMN. Regardless of the deviant type, the MMN latency and amplitude showed no significant differences due to EMF exposure on either side, showing no measurable effects on the preattentive change detection and automatic orienting response in either adults or children. No effects were found on auditory encoding (P1, N2) or involuntary attention shifting (P3a) in children.

In the MMN results, three slightly significant main effects were found, one in adults ($P = 0.045$) and two in children ($P = 0.045$ and 0.049) at the conventional alpha level of 0.05, but these main effects are likely to be chance findings due to multiple comparisons because all of them were rejected after adjustment for multiple comparisons. Simple methods such as Bonferroni corrections applied here could be often too conservative, but considering the number of comparisons and P-values, less conservative corrections would

lead to the same conclusion in these results. This conclusion was further supported by the statistically non-significant results of pairwise comparison between exposure conditions. At an alpha level of 0.05, one test has only a 5% chance to incorrectly reject the (true) null hypothesis but in 100 tests, for instance, it is expected that the (true) null hypothesis be rejected five times by chance. Therefore, it is necessary to apply conservative criteria as the number of tests or variables increases.

Finally, an important issue to be discussed here is effect size and statistical power. The ABR and MMN studies (II, III, IV) used the same sample size of 17 subjects, which is not considered small in EP/ERP studies. However, it may not be large enough to ensure sufficient statistical power to detect subtle effects of mobile phone radiation. In study IV, for instance, the estimates of effect size and observed power were small for the condition factor compared to those for the deviant factor, suggesting that, although the study was successful in detecting MMN responses to different deviants, it may not have had adequate statistical power to detect subtle changes due to exposure. Therefore, the present findings of null effects should also be replicated using a larger sample size.

CONCLUSIONS

This field of research has been full of controversies due to inconsistent and contradictory findings. More rigorous study designs such as crossover and double-blind protocols can reduce controversy. The issues of multiple comparisons, replication, and effect size and statistical power should also be taken into account.

The present series of studies aimed at detecting possible effects of mobile phone radiation by means of behavioral and neurophysiological methods, without involving any complex cognitive processes or performance. The exposure setup provided constant and reliable RF signals of a typical GSM mobile phone (902 MHz pulsed at 217 Hz with mean power of 0.25 W) throughout the experiments. The present series of studies found no measurable effects of short-term concurrent mobile phone radiation on the peripheral and central auditory processing reflected in the ABR and auditory ERP. In addition, there was no evidence for the ability to perceive mobile phone EMF in the general population.

ACKNOWLEDGEMENTS

I am most grateful to my supervisor Prof. Heikki Hämäläinen for his invaluable support and guidance since I first came to Finland to study for a Master's degree in 2002. I am also grateful to my coauthors, Matti Laine, Mika Koivisto, Teija Kujala, Minna Huotilainen, Risto Näätänen, Anna Shestakova, Satu Jääskeläinen, and Tim Toivo for providing their expertise and helpful comments. I thank Prof. Jukka Juutilainen and Prof. Patrick Haggard for reviewing the manuscript and providing constructive comments and suggestions. I also thank Prof. Pekka Niemi, the head of the Department of Psychology, for his encouragement and support.

I wish to thank all my colleagues at the Centre for Cognitive Neuroscience and the Department of Psychology. I am grateful to Mia Ek for all her help and kindness and to Valdas Noreika and Levente Móró for sharing moments and having interesting discussions. It was all my pleasure to work with Teemu Laine, Jyrki and Outi Tuomainen, Katja Valli, Victor Vorobyev, and many others.

Finally, I thank my parents and sister Aram in South Korea for their endless love, trust, and support. I also express gratitude to my warm-hearted Finnish parents, Aimo and Liisa Salminen. It was all possible because we were together, Taru.

This work was funded by Tekes, the Finnish Funding Agency for Technology and Innovation, and further supported by the Turku University Foundation, the Wäinö Edward Miettinen Foundation, and the Oskar Öflund Foundation.

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