Exposure to electromagnetic fields (EMF) from mobile phone signals and effects on human brain activity and neurobehavioral performance

217

Master Thesis
Date 12-01-2010

Student:	Maartje Brouwer
Studentnumber:	0357308
Masterprogram:	Toxicology and Environmental Health IRAS, Utrecht University
Institute:	Division EEPI, IRAS
Supervisor:	Pauline Slottje, Phd
Second reviewer:	Prof. Dr. ir. Hans Kromhout

Summary

During the last decades mobile phone use has been rapidly growing. In parallel public concerns about potential adverse outcomes of mobile phone use and exposure to electromagnetic fields (EMF) has also increased. Effects on human neurophysiological functioning are one of the areas of interest in this research field. This thesis attempts to present an overview of literature on neurophysiological effects related to EMF-RF exposure from mobile phone signals, with special attention to children who are suggested to be a specific sensitive group with regard to RF-EMF exposure.

Small alterations of alpha frequency spectral power on the EEG are consistently found for resting, sleep and EEG during cognitive processing, both during and after exposure to RF-EMF signals resembling GSM phone use. On neurobehavioral performance measures, rather inconstant results are published. The amount and quality of experimental studies including children is too limited to conclude that children are indeed more susceptible to EMF-RF exposure from GSM phone signals.

The small changes in brain oscillatory responses found during and after acute exposure to RF-EMF signals do not seem to be associated with comparable changes in behavioral performance measures. The clinical significance of these small changes in brain activity is difficult to determine. It can be concluded that acute RF-EMF exposure to the head, resembling GSM phone signals, is unlikely to affect human cognitive functioning. However, as only acute responses to relatively short RF-EMF exposures were investigated in laboratory settings, no information is present on potential long-term effects of (cumulative) RF-EMF exposure. If cumulative effects of RF-EMF exist, children should be considered to be a more vulnerable group at increased risk as their brain and central nervous system (CNS) are still in development and their skull is relatively thin. Therefore, future research should focus on potential long-term, cumulative effects of RF-EMF exposure and experimental studies should give more attention to potential mechanisms behind RF-EMF interaction with biological systems, improve the study designs and use standardized methodology.

List of abbreviations

CNS	Central Nervous System
EEG	Electro Encephalogram
ELF	Extremely low frequency
EMF	Electro-Magnetic Field
EP	Evoked potentials
ERD	Event Related Desynchronization
ERK	Extracellular-signal Regulated Kinase
ERP	Event Related Potentials
ERS	Event Related Synchronization
GSM	Global System for Mobile communication
MEG	Magneto encephalography
MHz	Mega-Hertz
MRI	Magnetic Resonance Imaging
MW	Microwave
NBTB	Neurobehavioral Test Battery
NREM	Non Rapid Eye Movement
REM	Rapid Eye Movement
RF	Radiofrequency
RT	Reaction Time
SAR	Specific Absorption Rate
UMTS	Universal Mobile Telecommunication System
WASO	Waking After Sleep Onset

Table of contents

1. Introduction

Since their introduction, more than a decade ago, the use of mobile phones has increased rapidly and became a popular form of electronic communication worldwide. Currently, the amount of connections exceeds the amount of inhabitants in the Netherlands. For every 100 inhabitants 113 connections were present in 2007 [(1)]. With this increased mobile phone use (and accompanying growth of mobile phone base stations), the public concern on potential harmful effects of every day exposure to radio frequency (RF) electromagnetic fields (EMF) has also increased, as these fields are emitted by mobile phones and other wireless communication devices. The RF-EMF emitted by mobile phones is absorbed through the skull to some extent, and the brain is exposed to this radiation [(2)]. Therefore a physiological interaction could be hypothesized between this RF-EMF and the human brain, altering physiology, activity and human behavior and functioning. While a potential link between (brain) tumors and RF exposure from mobile phone use was a primary concern, other potential RF-EMF related effects on the brain are currently also of scientific interest. Over the past years, several studies have investigated the effects of RF-EMF emitted by mobile phones on brain activity and neurobehavioral function in humans. As these abilities play an important role in everyday functioning, small alterations could have a significant impact on cognitive function and related health aspects. Especially when taking into account the large number of mobile phone users worldwide, even small adverse alterations of cognitive function could have major public health implications.

More devices, like mobile phone base stations and other wireless communication devices emit RF-EMF. However, mobile phones are of specific interest as this thesis will focus on human brain activity and neurobehavioral outcomes in relation to RF-EMF from mobile phone signals. Besides their widespread use, mobile phone exposure is localized at the head of an individual, resulting in high peak exposure values for the brain tissue at the side where the mobile phone is held during calling. Mobile phone use is therefore considered to be more relevant for the outcomes of interest, than for example continuous whole body exposure to RF-EMF from mobile phone base-stations.

The use of mobile phones is not limited to adults only. Children and adolescents are currently an important group of mobile phone users, and this use is starting at an increasingly younger age. A Danish cohort study reported exposure to mobile phones, although infrequently, in already 30% of the 7 year-olds in Denmark [(3)]. It is hypothesized that children should be regarded as a potentially susceptible group of individuals, as their brain and central nervous system (CNS) are still in development and their skull is relatively thin. Furthermore they are an active group of mobile phone users with high cumulative lifetime exposure to RF-EMF.

Although a large number of studies have been published that investigated the effect of RF-EMF emitted by mobile phones on brain activity and cognitive functioning, the reviews and conclusions on mobile phone use and health provided by different national authorities remain inconsistent. By making an inventory of available literature on the subject with an extensive and structured literature search, the aim of this thesis is to present a literature review on relevant studies investigating effects of RF-EMF exposure from mobile phone signals on brain activity and neurobehavioral performance.

1.1 Research questions

The main research questions that will be addressed in this literature review is the following: 'Is there evidence for effects of RF-EMF from mobile phone signals on brain activity and neurobehavioral performance, thereby impairing human cognitive functioning?'. This main research objective will be divided in smaller sections, in order to create a structured assessment of the main research question. The first sub-question is: 'What is the effect of RF-EMF from mobile phone signals, on human brain activity?' Furthermore, 'What is the effect of RF-EMF from mobile phone signals, on human neurobehavioral performance?' An issue resulting from these first two sub-questions is whether the effects of RF-EMF on brain activity and cognitive performance found in these studies, will have any practical implications for human cognitive functioning in every day life. There might be observations of small changes in brain function for example, but without any clinical, health or performance implications their relevance for public health and society is limited.

Another important aspect is taking into account the potential of more vulnerable groups in the population. For EMF-RF exposure, the assumption is made that children might be a specific group of interest. Therefore, a section in this literature review will be dedicated to the effect of RF-EMF exposure from mobile phone signals on brain activity and neurobehavioral performance in children and adolescents, to assess whether there are indications that children are indeed a more susceptible group of mobile phone users.

Before these research questions will be addressed (chapter 4), chapter 2 will provide background information on RF-EMF from mobile phones and the assessment of brain activity and neurobehavioral performance. Chapter 3 will describe the methods used in the literature collection and in chapter 5 the findings will be discussed.

2. Background

EMF are present everywhere in our environment, some visible (light), but most invisible to the human eye. They are an interaction between electric and magnetic forces. Natural sources of electric fields are produced by the local build-up of electric charges in the atmosphere associated with thunderstorms and the best known natural magnetic field surrounds the earth. But besides these natural sources, many man-made sources are present which generate EMF like x-rays, (high voltage) electricity and various kinds of high frequency radio waves which are used to transmit information.

2.1 EMF spectrum

EMF are waves with different wavelengths and frequencies. De frequency of EMF is generally expressed in Hertz (Hz). The higher the frequency, the shorter the wavelength and the more energy the field contains. The range of the EMF spectrum is depicted in figure 1. Frequencies between 0 and 3000 Hz are called extremely low frequency fields (ELF), for example the high power voltage electricity network makes use of such frequency (50Hz). Fields with a frequency of 0 are called static magnetic fields, and these fields are amongst others used for magnetic resonance imaging (MRI) technology. Above 3000 Hz are, in order of increasing frequency and decreasing wavelength, radio frequency (RF) waves and microwaves, optical radiation (infrared radiation, visible light and UV radiation) and ionizing radiation (UV radiation, x-rays and gamma x-rays). Comparing the strength of the different fields, microwaves have enough proton energy to heat tissue, while ionizing radiation like gamma x-rays can break chemical bonds thereby creating ions that can damage biological systems. Static and ELF EMF can induce weak electric currents in the body, but they do not have enough energy to either heat tissue or break chemical bonds [4].

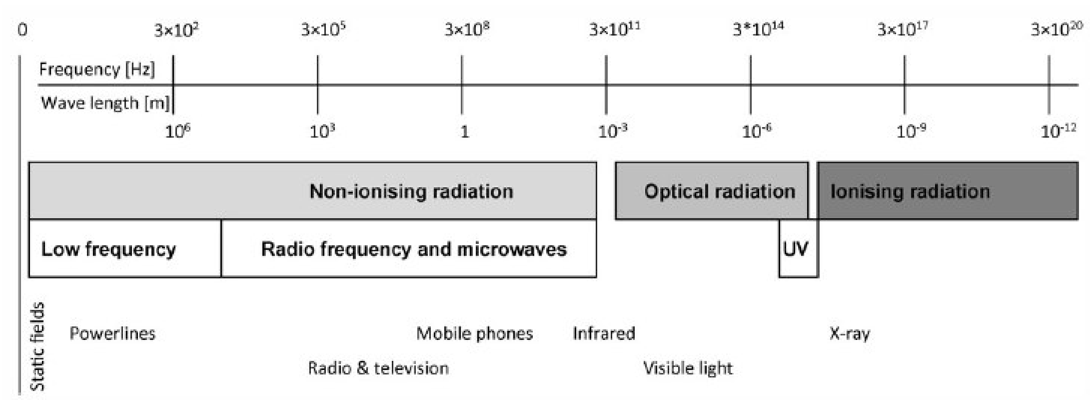

Figure 1. The EMF spectrum (adapted from Schuz et al. [5])

2.2 RF fields

The official definition of RF is that it is a band in the EMF spectrum that lies in the frequency range of 3 kHz to 300 GHz. Part of this band is microwave (MW) radiation which is generally considered to be a subset of RF, and MW covers 300MHz to 300GHz [(6)]. There are different sources of RF exposure to which people may be exposed, but the source of interest for this literature review is exposure related to mobile phone signals. Other common sources of exposure include mobile phone base-stations and radio and television transmitters operating at frequencies between 200 kHz and 900 MHz. Also occupational sources of RF-EMF exposure exist, for example RF PVC welding machines, plasma etchers and military radar systems. Mobile phones make use of frequencies from 450 to 2600 MHz. The first mobile phones available were systems operating between 450 and 900 MHz. The more recent third generation mobile phones make use of the Universal Mobile Telecommunication System (UMTS), which operates in the 1800-2600 MHz frequency range. New developments like future G4 phones, will work on much lower frequencies, below the 50 MHz range [(7)].

2.3 RF and health outcomes

The focus of this literature review lies on changes in human brain activity and differences in cognitive performance or other neurobehavioral endpoints, related to RF-EMF exposure. As the brain is most close to the mobile phone antenna and thereby to the source of the RF-EMF which penetrate the brain for a certain extent, effects of this radiation on the brain are therefore of particular scientific interest. Another important issue is a potential link between RF-EMF exposure from mobile phones and health and the risk of brain cancer. However, as mobile phone technology became available for the general public over more than a decade ago, and the extreme usage is something of more recent years, the population exposure is relatively short considering the long latency of malignant disease. Self-reported symptoms and hypersensitivity are other outcomes studied in relation to RF-EMF exposure. Especially sleep problems and headaches are commonly reported health complaints attributed to RF-EMF exposure. Besides the subjective nature of these outcomes, this research area mainly focuses on RF-EMF exposure related to mobile phone base-stations, and is therefore not included in this literature review.

2.3.1 Mechanisms of interaction

The hypotheses on mechanisms of interaction between RF-EMF and biological systems like the brain can be roughly divided into two groups. The first hypothesis is a thermal warming effect of the tissue exposed to RF-EMF. Microwave radiation is capable of producing heat, however, the rise in brain tissue temperature during exposure to RF-EMF from a mobile phone, is estimated to be very low (fractions of ℃) [(8)]. For example, a predicted worst-case brain temperature rise from use of different mobile phones (GSM/UMTS) was 0.25℃ [(9)].

Other groups consider this warming effect to be too small to induce changes in brain function and suggest a non-thermal effect of RF-EMF on the brain. For this hypothesis several potential scenarios are possible. It may be the case that RF-EMF from mobile phone signals (pulsed oscillatory signals) can directly interfere with brain electric oscillatory activity [(8)]. Other potential mechanisms mentioned are for example induction of DNA-damage by RF-EMF signals [(10)] and the activation of extracellular-signal regulated kinase (ERK) [(11)], which plays an important role in cell signalling. At this moment, there is no strong evidence for any of these hypotheses and it is not known how RF-EMF interacts with biological systems.

*2.*4 Neurophysiological outcomes

The brain is a complex system and small alterations in its functioning can be reflected in a large range of outcomes, from brain oscillation to motor-function. In relation to RF-EMF exposure, two main neurophysiological domains are investigated. First are changes in brain activity, determined by small alterations in the brains electrical currents (oscillatory activity). Besides physiological changes in the brain, also changes in neurobehavioral performance are an important area of EMF research [(12)].

2.4.1 Brain activity

One of the most common applied electrophysiological methods for investigating different aspects of brain function is the electroencephalogram (EEG). The EEG is a non-invasive method that records the currents or electrical activity of the brain through the scalp. EEG is typically described in terms of rhythmic brain activity and single events in the electric currents. The rhythmic activity of the brain is divided into bands with different frequencies. The alpha band (8-12 Hz) can be recorded from electrodes at the back of the head from the visual cortex, during rest or sleep. The alpha rhythm reflects a baseline cortical de-activation in rest and is associated with cognitive inhibition and visual relaxation and alpha power at 10 Hz is considered to reflect the transition from waking to sleep [(9)]. However this band can also be recoded during activities and tasks, implying that it is a rather unspecific response of the CNS [(12)]. The beta band (12-30 Hz) has been associated with motor function (e.g. movement and speech). The gamma band (30-100 Hz) is recorded during visual perception and object recognition. Finally the theta band (4-7Hz) is associated with working memory-processes [(13)].

The spontaneous EEG is recorded during rest (eyes closed) or sleep of the study objects. It reflects the natural spectral power of the different frequency bands when no exposure is present and can be compared with an exposure situation to examine for instance the effect of RF-EMF exposure. Sleep is also an often studied stage, as potential confounders in waking studies (e.g. alertness and motivation) are not an issue during sleep and brain activity follows a rather consistent pattern during sleep. Sleep is an essential part of human functioning and sleep deprivation for example, has a major impact on performance. Furthermore, sleep problems are among the most self-reported complaints related to RF-EMF exposure. Sleep is therefore of special interest and especially suitable to analyse the effects of RF-EMF on the brain activity by EEG [(14)]. Besides EEG measurements, RF-EMF effects on sleep are also assessed by the sleep architecture (different stages like REM and NREM sleep), measurement of differences in sleep latency or other sleep variables, like waking after sleep onset (WASO).

For studying cognitive processes in RF-EMF research, often the event-related potential (ERP) technique is used. The focus then is on the components of the EEG, related specifically to the presentation of stimuli (ERP). Event-related oscillatory EEG responses can be quantified, by means of the event-related desynchronization (ERD) method. In this method a relative decrease in the power of a certain frequency band during stimulus processing (compared to non-stimulus reference) is called ERD, while the opposite, a relative increase in power is called event-related synchronization (ERS) [(8)].

2.4.2 Neurobehavioral performance

Neurobehavioral performance tests are used in research to detect changes in central nervous system function resulting from a certain exposure. For each different cognitive domain, tests are developed and grouped in neurobehavioral test batteries (NBTB). In general, these NBTB are used in experimental designs (in a controlled environment) where volunteers are exposed to different levels or duration of exposure while performing certain tasks. Most tasks involve the recognition of targets and a subsequent response, and scoring is based on the reaction time (RT) of an individual and the accuracy of response. The most studied domains in RF-EMF research are ‘attention’ and ‘working memory’, but also executive functions such motor-function are assessed.

2.5 RF in experimental studies

2.5.1 Mobile phone signal

Different experimental settings are used, to investigate the influence RF-EMF exposure on brain activity and neurobehavioral performance. The frequencies of interest for RF-EMF related to mobile phone signals range from approximately 450 to 2600MHz. The most commonly studied of these frequencies is the 900 MHz Global System for Mobile Communication (GSM), but the number of studies including UMTS phones signals (1800-1900 MHz) has increased over the last years . Besides different frequencies used, also the pulse modulation (PM) of the signal can differ between studies. The aim of PM is to transfer a narrowband analog signal, like a phone call, over a wideband baseband channel or, in some of the schemes, as a bit stream over another digital transmission system. Mobile phone signals are pulsed at different frequencies, depending on their activity. A mobile phone has a basic pulse at a frequency of 217Hz. When a phone is actively used in ‘talk mode’, every 26 pulses are grouped together under another ELF pulse at around 8 Hz. Mobile phones making use of battery saving (DTX technology) have an additional pulse at 2 Hz during listening mode. In stand-by a phone will pulse less frequent to maintain contact with the base station [9]. Besides a PM signal, also a continuous wave (CW) signal can be used. This is an electromagnetic wave of constant amplitude and frequency. Early generation analogue phones, made use of such a CW signal, but these were rapidly replaced by digital GSM, making use of PM signals.

Another important parameter is the specific absorption rate (SAR) specific for RF-EMF exposure from mobile phone signals. SAR is the defined as the RF power or energy flow absorbed per unit of mass (watts(W)/kg), and represents the power or heat absorbed by the tissue either in a local area of a human tissue or averaged over the whole body. The local peak SAR levels inside the human head differ depending on many factors, including antenna characteristics, distance to the source of radiation and characteristics of the exposed participant. In many RF-EMF studies a calculation of the SAR is presented as a metric of field intensity and dose [2]. The strength of the field emitted differs per mobile phone. There are guidelines however, describing the maximum SAR levels allowed. In the European Union (EU) the limit is set to be 2 W/kg averaged over ten grams of body tissue, and therefore this is the maximum to which a individual will be exposed when using a mobile phone [15].

2.5.2 Other exposure parameters

For RF-EMF research, the challenge is to translate everyday mobile phone use to an experimental exposure scheme. Participants can be exposed on the right hemisphere, on the left or in the middle of the head. The duration of exposure and timing are also important. The duration of exposure in experimental studies is often longer than average calling time. Actual mobile phone use consists of multiple short exposure events throughout a certain time period, but this is often not feasible in experimental design. As most studies use a single exposure event, relatively long exposure duration is chosen to resemble a total day-exposure. Furthermore, studies can be single or double blinded, of which the latter is preferred as both researcher and participant do not know when exposure takes place and are less likely to influence the outcome of the study. In RF-EMF research most studies apply a cross-over design where the subjects are exposed to both sham and RF-EMF conditions. The individuals acts as their own control, thereby minimizing the influence of inter-person variation on study outcomes compared to designs with different exposure groups.

As it is currently not known which parameters are most important for RF-EMF interaction with biological systems, and whether cumulative exposure might play a role, it is difficult to establish a reasonable worst-case approach for experimental studies.

3. Material and methods

For this literature review on neurophysiological effects of RF-EMF from mobile phone signals, the databases of Scopus and Pubmed were searched for relevant experimental studies and reviews, published before 1 December 2009. The main search terms describing the exposure "electromagnetic field (EMF)", "radiofrequency field (RF)", "mobile phone" or "cell phone" were combined with several search terms describing the outcome of interest. Studies addressing RF-EMF exposure from mobile phone base-stations were excluded, as the focus of this thesis lies on (local) exposure by mobile phone signals. The outcomes of interest were defined as "neurophysiology", "(neuro)behavioral performance", "cognitive function", "memory", "performance measures" and "brain activity", of which the latter was combined with different terms describing the state of the study subjects ("sleep", "resting", "awake") and the measurement methods used ("electro-encephalogram (EEG)", "event related potential (ERP)" or "evoked potential (EP)").

For the more specified search on RF-EMF effects on children, "children" or "adolescents" were included in the search terms. As this literature review will focus on exposure and related outcomes in humans, studies describing experiments in animal models were excluded from the search. Studies were only included when the subjects enrolled in the study were considered to be healthy. Studies on narcoleptic and epileptic patients were excluded, as findings in those groups will be difficult to extrapolate to the general population.

Furthermore, if the full-text was not accessible, the article was excluded. Evaluation of the articles consisted of two steps. First the abstract was evaluated for consistency with the topic of interest, and second all obtained articles were read with a main focus on the described outcomes and the methodology and experimental design.

4. Results

4.1 RF and brain activity

4.1.1 Resting EEG

Several studies have assessed the effect on RF-EMF exposure from mobile phones on brain activity in rest and are summarized in table 1. The first to carry out such an experiment were Reiser *et al.* in 1995 [16]. After 15 minutes exposure to a GSM signal (902.4 MHz, PM 217 Hz), an increase in EEG power was observed for the fast alpha (9.75-12.5Hz), slow beta (12.75-18.5Hz) and fast beta (18.75-35.0Hz) bands. Roschke and Mann [17] conducted an experiment with a similar exposure as used in Reiser *et al.* [16]. They assessed the effect of a very short exposure session (3.5 minutes) and found no changes in the EEG spectral power analyses. Hietanen *et al.* [18] also failed to find any effect of RF-EMF exposure (5 different mobile phones, operating between 900 MHz and 1800 MHz) on resting EEG.

Huber *et al.* [19] used two different mobile phone signals in their 2002 study, a CW-signal and a PM-signal. In the resting stage prior to sleep, 30 minutes exposure to PM-EMF was observed to enhance EEG power in the alpha frequency range (peak at 10Hz). The authors concluded that pulse modulation was necessary to induce changes in waking (and sleep) EEG, as the CW-EMF exposure did not resulted in any changes. Croft *et al.* [20] exposed their volunteers to a standard Nokia phone (900MHz, PM 217 Hz) for three times 20 minutes, and observed a significant increase in alpha activity (8-12 Hz) and a significant decrease in delta activity (1-4 Hz). In a 2003 study by Kramarenko and Tan [21] resting participants were exposed to a 900 MHz PM signal. After exposure, abnormal slow waves (2.5-6Hz) were observed in the delta range with a latency of 20-40 seconds after exposure. These waves progressively decreased after the signal ended, suggesting a reversible effect. For the children, similar changes were found, but the observed slow waves appeared earlier (latency 10-20 seconds) in children than adults and their frequency was lower (1.0-2.5Hz), with longer duration and shorter intervals. D'Costa *et al.* [22] examined the EEG from 10 subjects taken during exposure to RF-EMF (900MHz, PM 217 Hz). An intermittent exposure scheme was used of 5 minute intervals with a random sequence of 5 sham and 5 active exposures, over the midline cortical region. Significantly higher alpha (8-13Hz) and beta (13-32Hz) activity was found during active exposure. Noteworthy was the non-significant decrease of spectral power in the stand-by mode of the phone. Using exposure conditions (900 MHz, PM 217Hz) similar to previous studies, Curcio *et al.* [23] also observed a change in the EEG spectral power of the alpha band. This study had two EEG recoding scenarios, during the first exposure (45 minutes) took place prior to the EEG recording and for the second RF-EMF was on during the EEG recording. In both cases, the spectral power of the alpha band was increased, but this effect was larger when exposure took place during the EEG, with an additional spectral power peak at 11 Hz. A more recent study by Kleinlogel *et al.* [24] exposed the study objects to both

GSM (900 MHz, PM) and UMTS (1950 MHz) signals for 30 minutes. No changes in spectral power were observed during the resting EEG.

Two other recent studies by Hinrikus *et al.* [25, 26] do report alterations in the alpha and beta bands after EMF exposure in the microwave (MW) range of 450Hz. This frequency is at the lower range of frequencies used in mobile phone technology. In the first study [26], the 450Hz MW signal was pulse modulated at 3 frequencies, 7, 14 and 21 Hz. The MW signal modulated at 14 and 21 Hz enhanced the EEG power in the alpha wave and beta wave frequencies whereas no change of the EEG power was found during exposure to the 7 Hz modulated signal. The effect of modulated microwaves on the EEG differs at different modulation frequencies, and the authors suggest that the effect of an external stimulus on brain oscillations is stronger if the frequency of the stimulus is higher or close to the physiological frequency of brain rhythms. The second [25] study expanded with 7 modulating frequencies, ranging from 7 to 1000 Hz. The MW exposure increased the EEG energy at EEG frequencies lower or close to the MW modulation frequency (different modulation frequencies affected different EEG frequency bands). No effect was found at EEG frequencies higher than the modulation frequency. Significant alterations were observed in the EEG beta wave frequency bands.

Table 1. Overview of studies investigating effects of RF-EMF on brain activity during rest by EEG.

Study	Study subjects (n)*	Exposure **	Duration	Blinding	Main outcomes
Croft *et al.* [20]	16 M, 8 F	900 MHz PM 217 Hz -	3 x 20 min	Single	Increase alpha, decrease delta power
Curcio *et al.* [23]	10 M, 10 F	902.4 MHz PM 217 0.25 W/kg	45 min	Double	Increase EEG power alpha band (effect larger for EMF on during EEG)
D'Costa *et al.* [22]	5 M, 5 F	900 MHz PM 217 -	5 x 5 min	Single	Decrease alpha and beta power
Hietanen *et al.* [18]	10 M, 9 F	900, 1800 MHz	20 min	Single	No effects
Hinrikus *et al.* [26]	30 M, 36 F	450 MHz PM 7, 14 & 21, 40 & 70, 217, 1000 Hz 0.303 W/kg	20 min	Double	Alteration alpha and beta rhythm
Hinrikus *et al.* [25]	4 M, 9 F	450 MHz PM 7, 14, 21 Hz 0.35 W/kg	40 min	Double	Increase in alpha and beta rhythm (for PM 14 & 21 Hz)
Huber *et al.* [19]	16 M	900 MHz CW & PM 2, 8, 217, 1736 Hz 1 W/kg	30 min	Double	Alpha power increase, PM signal
Kleinlogel *et al.* [24]	15 M	900, 1950 MHz PM 217 Hz 1 W/kg	30 min	Double	No effects
Kramarenko *et al.* [21]	10 M (adults), 10 M (12 yr)	900 MHz PM 217 Hz -	Duration of a call	-	Abnormal slow waves in delta range
Reiser *et al.* [16]	18 M, 18 F	902.4 MHz PM 217 Hz -	15 min	Single	Increase in EEG power in alpha and beta band
Roschke *et al.* [17]	34 M	900 MHz PM 217 Hz -	3.5 min	Single	No effects

* M – males, F – females ** exposure parameters given are frequency (MHz), pulse modulation (PM) frequency and estimated average field intensity W/kg (SAR)

4.1.2 Sleep EEG

Sleep is also an often studied stage in RF-EMF research. During sleep, potential confounders as identified for waking studies (e.g. alertness and motivation), are less of an issue. Studies of RF-EMF exposure and EEG spectral power will be discussed below and a separate section deals with sleep architecture. These studies are summarized in table 2.

Mann *et al.* [(27)] were the first to assess the potential effects of RF-EMF exposure (900MHz, PM 217 Hz) on human sleep EEG in an early cross-over study. Study objects were exposed overnight (8 hours) to a source mounted at 40cm of the subjects head. RF exposure was found to increase spectral power density of the EEG signal during REM sleep, which was significant in the alpha band. When the same group tried to replicate these latter findings in a second study, they failed [(28)]. Differences in exposure methods (different antenna and location of the source) were mentioned as potential explanations. In a third study from this group [(29)], the maximum allowed SAR was applied (50W/m^2, 1.8W/kg), but no effects on spectral power and conventional sleep parameters were observed.

Borbely *et al.* [(30)] investigated the effect of an intermittent exposure scheme (15 min sham, 15 min RF-EMF) on the brain of healthy young men (20-25 years) during an entire night-time sleep episode. Spectral power of the EEG was increased in NREM sleep in the alpha (10-11 Hz) and sigma (13.5-14Hz) bands. Huber *et al.* [(31)] reported similar results. In this study, exposure to a PM 900 MHz signal was now restricted to a 30 minute period before sleep, but also an increase alpha (9.75-11.25Hz) and sigma (13.5-14Hz) band power during the first 30 minutes of NREM sleep was observed. Subjects were exposed to both a 900 MHz PM signal and a CW signal, but no effects were observed for the CW. In a follow-up study, Huber *et al.* [(19)] extended their EEG analysis to periods preceding sleep onset, while keeping other parameters similar to the previous study [(31)]. After 30 min of exposure, enhanced EEG power was observed in the alpha range prior to sleep onset and this continued into the sleep period, increasing alpha activity in the NREM stage. In addition, an increase in EEG alpha activity was observed during waking before sleep onset. Again, exposure to RF-EMF without pulse modulation did not enhance power in the waking or sleep EEG.

In 2005, Loughran *et al.* [(32)] used the same study design as Huber *et al.* [(19, 31)], but included a larger number of participants (n=50). These participants were exposed to 30 minutes of RF-EMF (894.6 MHz, PM), 30 minutes before a night-time sleep episode. The results confirmed an increase of alpha power (11.5-12.25 Hz) in the first 30 minutes of NREM sleep. Another study by Huber *et al.*[(33)] investigated the effect of RF-EMF exposure on both night-time as daytime sleep in two experiments. Participants were exposed to a 900MHz PM signal, for either intermittent 15 minute on/off exposure during the whole nighttime sleep period, or a 30 minute exposure prior to a 3 hour day-time sleep. Both experiments showed a significant increase in alpha activity (9-14 Hz) after RF-EMF exposure in the NREM stage. Furthermore, no differences in exposure side (unilateral or whole head) or duration of exposure were observed. In the most recent study, Regel *et al.* [(34)] exposed healthy male subjects to EMF

(900 MHz PM) signals with two strengths (SAR 0.1W/kg and 5 W/kg) in a double blind crossover design. Sleep EEG revealed a dose-dependent increase of power in the alpha (10.75–11.25 Hz) and sigma (13.5– 13.75 Hz) spindle frequency range in NREM sleep.

Table 1. Overview of studies investigating effects of RF-EMF on brain activity during sleep and sleep architecture.

Study	Study subjects (n)*	Exposure **	Duration ***	Blinding	Main outcomes
Borbely *et al.* (30)	24 M	900 MHz PM 2,8, 217, 1736 Hz 1 W/kg	8 hour, intermittent (15 min on/off)	Double	Increase of alpha and sigma power in NREM stage, WASO reduced
Huber *et al.* (31)	16 M	900 MHz CW & PM 2, 8, 217, 1736 Hz 0.14 W/kg	30 min prior to sleep	Double	PM signal, increase alpha and sigma power in NREM stage
Huber *et al.* (19)	16 M	900 MHz CW & PM 2, 8, 217, 1736 Hz 1 W/kg	30 min prior to sleep	Double	PM signal, increase alpha power in NREM stage
Huber *et al.* (33)	24 M, 16 M	900 MHz PM 2, 8, 217, 1736 Hz 1 W/kg	8 hour, intermittent or 30 min prior to sleep	Double	Increase alpha activity in NREM stage for both exposure regimes, WASO reduced during intermittent exposure (order-effect)
Hung *et al.* (9)	10 M	900 MHz PM 2, 8, 217 Hz 0.13 mW/kg	30 min prior to sleep	Single	Sleep onset delayed by talk mode (PM 8 and 217 Hz)
Loughran *et al.* (32)	27 M, 23 F	894.6 MHz PM 217 Hz 0.11 W/kg	30 min prior to sleep	Double	Increase alpha power in NREM stage, reduced latency REM sleep
Mann *et al.* (27)	12 M	900 MHz PM 217 Hz -	8 hour, continuous	Single	Increase alpha band power REM sleep, reduction duration and percentage REM sleep
Regel *et al.* (34)	15 M	900 MHz PM 0.1 W/kg, 5 W/kg	30 min prior to sleep	Double	Increase alpha and sigma power NREM stage, no effects on sleep architecture
Wagner *et al.* (28)	24 M	900 MHz PM 217 Hz 0.3 W/kg	8 hour, continuous	Single	No effects
Wagner *et al.* (29)	20 M	900 MHz PM 217 Hz 1.8 W/kg	8 hour, continuous	Single	No effects

* M – males, F – females ** exposure parameters given are frequency (MHz), pulse modulation (PM) frequency and estimated average field intensity W/kg (SAR)

4.1.3 Sleep architecture

Besides effects on spectral power of the different bands and brain activity, sleep research also involves the architecture of sleep and onset of the different sleep stages is often assessed. In the 1996 study by Mann *et al.* [27] a suppressive effect of RF-EMF exposure on sleep was reported, with a reduction of duration and percentage of REM sleep. However, to subsequent studies from the same group report no significant effects of RF-EMF on any of the sleep parameters [28, 29]. Borbely *et al.* [30] also found an effect on sleep architecture, contradicting previous results from Mann *et al.* [27]. The amount of WASO was reduced compared to sham exposure from 18 to 12 min, which indicates that RF-EMF exposure promotes sleep. A subsequent paper of the same laboratory [33] also reported reduced WASO. However, this effect was only observed in the group receiving whole night intermittent exposure and the effect was order-specific. Subjects exposed to sham first had a larger decrease in WASO compared to subjects with first exposure to EMF.

Loughran *et al.* [32] reported that EMF exposure reduced latency of REM sleep, promoting REM sleep onset. A more recent study of Hung *et al.* [9] found in contrast that the talk mode of a 900 MHz GSM phone (8 and 217 Hz pulse) significantly delayed sleep onset compared to the listen-mode (2, 8, 217 Hz pulse) and sham condition. Another study performed in 2007 by Regel *et al.* [34] revealed no effects of RF-EMF exposure on sleep architecture however.

4.1.3 EEG during cognitive processes

As effects of RF-EMF on spontaneous EEG may be very different from effects on brain activity during cognitive processes, EP are also often studied in relation to RF-EMF and health. Several studies use ERP as dependent variable, or ERS and ERD as a measure of changes in brain activity during cognitive processing.

Eulitz *et al.* [35] recorded EEG during an auditory discrimination task (also referred to as an oddball paradigm), with or without exposure to PM EMF. This study reported an effect of EMF exposure on the beta band (18.75–31.25 Hz), during the processing of target stimuli. Another task on cognitive visual monitoring was administered by Freude *et al.* [36]. Whereas the subjects' performance did not differ between the EMF exposure condition (916.2 MHz, PM) and sham, EMF did influence the slow brain potentials (SP). Exposure resulted in a significant decrease of SPs. Freude *et al.* [37] repeated their previous experiment with two additional tasks in 2000. They replicated the previous effects observed for the visual monitoring task, but no effects of EMF exposure on the EEG recordings were found for the other two tasks.
Krause *et al.* performed a number of studies on brain activity and EMF exposure. Their first study [38] investigated the effect of exposure to a mobile phone (902 MHz, PM 217 Hz) on brain activity, during a visual working memory task. ERS and ERD were examined at several EEG bands. The significant alterations of the EEG oscillatory responses around the theta (6-8 Hz) and alpha (8-10Hz) bands, indicated that EMF exposure can significantly modify brain responses during a (memory) task. A second study [39], making use of a similar memory task, replicated these findings. In 2004, Krause *et al.* [40] attempted to replicate their earlier work [39] investigating the effect of EMF (902 MHz, PM 217Hz) on EEG responses during a memory task, adapting a double-blind study design. No significant effects on oscillatory responses could be observed in this replication study. The only consistent finding between the present and the previous study was that in both studies electromagnetic fields decreased the magnitude or the ERS responses in the 4-6 Hz frequency band.
In a second attempt to replicate previous findings [39] [40], Krause *et al.* [8] administered both a visual and an auditory memory task to participants. EMF exposure was to both a PM and a CW signal, at the left or the right side of the head. The only statistically significant effect was

Table 3. Overview of studies investigating effects of RF-EMF on brain activity during cognitive processing.

Study	Study subjects (n)*	Exposure **	Duration	Blinding	Main outcomes
Bak *et al.* [41]	13 M, 12 F	450, 935 & 1800 MHz PM 217 Hz -	During task	-	No effects
Croft *et al.* [20]	16 M, 8 F	900 MHz PM 217 Hz -	During task	Single	Increase alpha activity, decrease in delta band
Eulitz *et al.* [35]	13 M	916.2 MHz PM 217 Hz -	During task,	Single	Effect on beta band during processing of stimuli
Freude *et al.* [36]	16 M	916.2 MHz PM 217 Hz 1.42 mW/kg	During task	Single	Decrease slow brain potentials
Freude *et al.* [37]	16 M	916.2 MHz PM 217 Hz 1.42 mW/kg	During task	Single	Decrease slow brain potentials in visual monitoring task (no effect on other 2 tasks)
Hamblin *et al.* [42]	4 M, 8 F	894.6 MHz PM 217 Hz 0.11 W/kg	Prior to task	Single	Auditory EP amplitude and timing altered
Hamblin *et al.* [43]	46 M, 74 F	894.6 MHz PM 217 Hz 0.11 W/kg	Prior to task	Double	No effects
Hinrichs *et al.* [44]	2M, 10 F	1800 MHz PM 217 Hz 0.61 W/kg	During task (partially)	Double	Alteration EP timing
Hountala *et al.* [45]	19 M, 20 F	900, 1800 MHz CW -	During task	-	Differences in SPC between males and females disappeared when exposed to 900 MHz, and reversed for 1800 MHz
Kleinlogel *et al.* [46]	15 M	900 & 1950 MHz PM 217 Hz 1 W/kg	During task	Double	No effects
Krause *et al.* [38]	16 M	902 MHz PM 217 Hz -	During task	Single	Increase theta and alpha band power
Krause *et al.* [39]	24 M	902 MHz PM 217 Hz -	During task	Single	Increase theta and alpha band power
Krause *et al.* [40]	12 M	902 MHz PM 217 Hz 0.878 mW/kg	During task	Double	No effects
Krause *et al.* [8]	36 M	902 MHz CW & PM 217 Hz 1.1 W/kg	During task	Double	Difference alpha response during auditory memory task between PM and CW signal (not with sham)
Maby *et al.* [47]	3 M, 6 F	900 MHz PM 217 Hz 1.4 W/kg	During task	Single	Alteration EP amplitude and timing
Nanou *et al.* [48]	9 M, 10 F	900 MHz PM 217 Hz -	During task	-	Total EEG energy decrease in males, increase in females.
Nanou *et al.* [49]	10 M, 10 F	1800 MHz CW -	During task	-	EEG energy beta band larger in females than males during exposure
Oysu *et al.* [50]	18 M	900 MHz PM 217 Hz 0.82 W/kg	During task	Single	No effects
Papageorgiou *et al.* [51]	9 M, 10 F	900 MHz -	During task	-	Total EEG energy decrease in males, increase in females.
Vecchio *et al.* [52]	10 M	902.4 MHz PM 217 Hz -	During a 'call'	Double	EEG energy alpha band altered during exposure
Yuasa *et al.* [53]	5 M, 7 F	800 MHz PM 0.054 W/kg	Prior to task	-	No effects

* M – males, F – females ** exposure parameters given are frequency (MHz), pulse modulation (PM) frequency and estimated averga field intensity W/kg (SAR)

observed during the auditory working memory task between the pulse modulated and continuous wave exposure conditions. Larger alpha wave ERS and smaller alpha wave ERD responses were recorded during the pulse modulated exposure condition as compared to continuous wave exposure condition. As the authors conclude “the effects on the EEG ERD/ERS responses were however, varying, unsystematic and inconsistent with previous reports”.

Croft *et al.* [(20)] used a standard Nokia mobile phone (900MHz, PM 217 Hz) to assess subjects performance on an auditory discriminating task. Mobile phone exposure was found to significantly increase alpha activity (8-12 Hz), while significantly decreasing the delta (1-4Hz) activity over the right hemisphere. Papageorgiou *et al.* [(51)] assessed EEG changes during a memory task in response to a 900 MHz EMF. Subjects were randomly exposed to sham and exposure conditions, 45 min, separated for 2 weeks. Male subjects had significantly higher overall EEG energy then females at baseline. A significant difference between male and female participants was observed. EMF exposure resulted in a decrease of overall EEG energy in male subjects and an increase of overall EEG energy in female subjects during the memory task.

Hamblin *et al.* [(42)] examined the effect of an 894.6 MHz (PM 217 Hz) mobile phone on sensatory processing using an auditory evoked potential (EP) in an oddball task. It was found that auditory EP amplitude at N100 was reduced and the N100 and P300 waves were delayed in response to non-targets in the EMF exposure relative to sham. This study also suggests that there may be delayed effects of EMF exposure, as the EMF was turned on for an hour during the practice trails and turned off at the beginning of the trail test. However, a second study from the same laboratory [(43)] failed to replicate these earlier findings in a larger sample of subjects and with a double blind study design. No significant effects were found of EMF exposure on any visual of auditory ERP component or RT.

Hinrichs *et al.* [(44)] examined the effect of exposure to a 1800 MHz GSM (217 Hz pulsed) on verbal memory coding, measured by MEG. To reduce artefacts from the EMF exposure, active and sham exposures took place during the encoding part of the memory task. MEG waveforms are different from EEG, but the effect observed corresponds to a change in the P300 time in EEG. Maby *et al.* [(54)] reported similar findings in the sensory component N100 (a reduction in amplitude and latency), but the small size of this study is limiting (n=9). Yuasa *et al.* [(53)] also investigated sensory evoked potentials and their recovery function and found no effects after 30 minutes exposure to a pulsed 800 MHz GSM handset. Also no effects were found in other studies by Bak *et al.* [(41)] and Oysu *et al.* [(50)]. A study by Kleinlogel *et al.* [(46)] also found no evidence for any effect of exposure to a 1950 MHz UMTS signal and a PM 900MHz GSM signal. No effects of RF-EMF were found on ERP during visual, auditory and continuous performance tasks or during an oddball task.

Nanou *et al.* [48] observed that exposure to EMF (GSM 900 MHz), reduced the overall spectral power of the males EEG while increasing the female EEG. The males did have higher EEG energy at baseline. These changes in the EEG power spectrum induced by EMF seem to be gender dependent, and these observations are in line with Papageorgiou *et al.* [51]. In a recent second study, Nanou *et al.* [49] repeated the experiment with an 1800 MHz mobile phone. The analysis revealed that in the presence of EMF, the energy of the beta-band was significantly greater for females than for males.

Vecchio *et al.* [52] used a different study design. Not a performance task was administered, but EEG was recorded during a “mobile phone call” condition in which participants were asked to behave as they would during a normal phone call. Results showed that, GSM exposure modulated the alpha frequency band (8-12Hz) compared to the sham condition. Hountala *et al.* [45] investigated the effect of 900 and 1800 MHz EMF exposure during an auditory memory task on EEG spectral power coherence (SPC), which reflects the pattern of coordination of the four basic EEG bands. Delta rhythm was observed to be less consistent the other four rhythms. Furthermore, it has been shown that the EMF affected SPC differently for the two genders. In the absence of EMF, males exhibit higher overall SPC than females. These differences disappeared during 900 MHz exposure and were reversed when exposed to 1800 MHz.

4.2 RF and neurobehavioral performance

An overview of the studies investigating the effect of RF-EMF exposure on neurobehavioral performance is presented in table 4. Whereas Freude *et al.* [36] observed a significant effect of EMF exposure on slow brain potentials during EMF exposure, no effect of EMF exposure on performance during the visual monitoring task could be observed. In the second study [37] also no effect of EMF on performance on this task was observed, neither on performance on the two other tasks administered. Memory load and attention were assessed by Hladky *et al.* [55], but also for these tasks no impact of RF exposure on performance and reaction time (RT) could be found.

Preece *et al.* [56] did found a small decrease in reaction time in choice reaction task. During 30 minutes exposure to 915 MHz (CW and PM), 10 cognitive tasks were examined. Only for the choice reaction time a difference (decrease in reaction time) was observed during EMF exposure. Remarkably, this increase was larger for the CW signal compared to the PM signal (in contrast to findings by Huber et al. [19, 31]). Keetley *et al.* [57] showed that RF-EMF exposure resulted in impairment of performance on simple choice and reaction tasks, while performance on trail making was improved. No reasonable explanation could be given why opposing outcomes were found for these tasks.

Koivisto *et al.* [58] observed that RT in working memory tasks decreased during exposure to 900MHz mobile phone exposure. In a subsequent study, this finding could not be replicated [59]. In this study RT in a simple reaction task and vigilance tests increased. In contrast, cognitive time to complete an arithmetic task, decreased. However, when an independent expert group applied a more appropriate analysis to the data, only RT in the vigilance task was significantly increased. In an attempt to replicate and extend on the studies of Koivisto *et al.* [58, 59], Haarala *et al.* [60, 61] administered a NBTB of nine cognitive tasks to participants using the same mobile phone parameters (GSM 900 MHz, PM 217 Hz). Improvements were made by using a larger sample size (n=64) and a double blinded study design. They were unable to find any significant difference in cognitive function after RF-EMF exposure and previous results could not be replicated.

Lass *et al.* [62] administered 3 tasks on short-term memory and attention to 100 students. Groups were randomly assigned to either sham or PM 450MHz MW radiation. In the less complicated task, a significant decrease in the number of errors was observed. For the two other more tasks a significant increase in error variance between the exposed and non-exposed group was found. Another study in 2002 [20], failed however to find any effect of RF-EMF on performance and RT during an auditory discrimination task.

Edelstyn *et al.* [63] exposed their participants to a 900 MHz mobile phone for 30 minutes, and before, during and after exposure tasks were performed. A significant effect was observed in the group exposed to RF-EMF before the task. The subjects had improved working memory capacity and sustained attention, indicating that performance was facilitated after RF-EMF exposure. Similar facilitating effects of RF-EMF exposure were reported by Smythe *et al.* [64], after 15 minute exposure to an 1800MHz mobile phone, but the effect was restricted to the male participants. Males exposed to the active mobile phone made fewer errors than those exposed to the inactive phone. Another study reporting a mild facilitating effect of RF-EMF exposure was performed by Lee *et al.* [65]. After 25 minutes exposure to a 1900 MHz mobile phone, they recorded that RT in the sustained attention task decreased and performance in this task was increased. Such decrease in RT was consistent with findings in earlier studies by Koivisto *et al.* [58] and Preece *et al.* [56].

Curcio *et al.* [66] divided 20 subjects to two groups, one group was exposed for 45 minutes to RF-EMF (902.4MHz, PM) before simple choice and reaction tasks, while the other group was exposed during the tasks. Both EMF conditions resulted in significantly faster RT. However, subjects exposed 45 minutes prior to the tasks displayed significantly faster RT than those subjects exposed during the testing period. Maier *et al.* [67] found however, that RF-EMF exposure (902 MHz, PM) impaired participants cognitive performance. Performance on an auditory discrimination task was significantly impaired in 9 out of 11 subjects compared to the control condition. Krause *et al.* [40] also observed impaired performance as EMF exposure resulted in a significant increase in errors. They previously reported no significant effect of EMF exposure on the number of incorrect answers in the memory task [38] and therefore conclude that the effect of RF-EMF on the number of incorrect answers in the memory task was inconsistent.

While Papageorgiou *et al.* [51] reported on gender-related differences in the EEG during a memory task, no effect of RF-EMF on performance was observed, nor differences in performance between males and females. In their first study, Hamblin *et al.* [42] reported an increase in RT in the EMF exposure condition compared to sham, while no effect of RF-EMF on accuracy where found during the auditory task. However, the second study [43] observed no effects of RF-EMF exposure on RT during an auditory and visual task. Hinrichs *et al.* [44] were also unable to find a difference in performance on a verbal memory encoding task between EMF (1800 MHz, PM) and sham exposure. Schmid *et al.* [68] also used an UMTS signal (1970 MHz) in their study. Four clinical tests were administered to assess the effects of RF-EMF exposure on visual perception. No effects of UMTS exposure on this cognitive domain could be found. Kleinlogel *et al.* [24] exposed their participants to both GSM 900MHz and UMTS 1950MHz. They found no effect of these exposures on the assessed behavioral parameters, RT and accuracy of the response.

Besset *et al.* [69] exposed participants for 120 minutes to a mobile phone (900MHz, PM 217 Hz). Thirteen hours after exposure, testing was done the next day. No effects of RF-EMF were found in the neuropsychological categories information processing, attention capacity, memory function and executive function. The authors conclude that the longer time between exposure to the mobile phone and the subsequent testing may have allowed for recovery of function. Eliyahu *et al.* [70] reported a slowdown in RT in three out of four spatial and verbal recognition and spatial compatibility tasks, after exposure to a 890MHz PM phone signal. However, this effect was only significant for one task.

Table 4. Overview of studies investigating effects of RF-EMF on neurobehavioral performance.

Study	Study subjects (n)*	Exposure **	Duration	Blinding	Tasks (n)	Main outcomes
Besset *et al.* [69]	27 M, 28 F	900 MHz PM 217 Hz	120 min, day before tasks	Double	15	No effects
Croft *et al.* [20]	16 M, 8 F	900 MHz PM 217 Hz -	During task	Single	1	No effects
Curcio *et al.* [66]	10 M, 10 F	902.4 MHz PM 8, 217 Hz 0.5 W/kg	Prior and during task	Double	4	Improvement RT in 2 tasks, effect larger in group exposed prior to task
Curcio *et al.* [71]	12 M, 12 F	902.4 MHz PM 8, 217 Hz 0.5 W/kg	Prior to task	Double	2	No effects (non-significant trend to shorter RT during exposure)
Edelsteyn *et al.* [63]	38 -	900 MHz PM -	Prior and during task	Single	6	Decrease in RT in 2 tasks in group exposed prior to tasks
Eliyau *et al.* [70]	36 M	890 MHz PM 217 Hz	During task	Single	4	Increase in RT in 1 task
Freude *et al.* [36]	16 M	916.2 MHz PM 217 Hz 1.42 mW/kg	During task	Single	1	No effects
Freude *et al.* [37]	16 M	916.2 MHz PM 217 Hz 1.42 mW/kg	During task	Single	3	No effects
Haarala *et al.* [60]	32 M, 32 F	902 MHz PM 217 Hz 0.88 W/kg	During task	Double	9	No effects
Haarala *et al.* [61]	32 M, 32 F	902 MHz PM 217 Hz 0.88 W/kg	During task	Double	1	No effects
Haarala *et al.*	36 M	902 MHz	During task	Double	4	No effects

[72]		CW & PM 217 Hz 1.1 W/kg				
Hamblin *et al.* [42]	4 M, 8 F	894.6 MHz PM 217 Hz 0.11 W/kg	Prior and during task	Single	1	Increase RT
Hamblin *et al.* [43]	46 M, 74 F	894.6 MHz PM 217 Hz 0.11 W/kg	During task	Double	2	No effects
Hinrichs *et al.* [44]	2M, 10 F	1800 MHz PM 217 Hz 0.61 W/kg	During task	Double	1	No effects
Hladky *et al.* [55]	20 M	900 MHz PM 217 Hz 0.1 W/kg	During task	-	2	No effects
Keetley *et al.* [57]	58 M, 62 F	900 MHz PM 217 Hz -	During task	Double	8	Performance on simple choice and reaction task decreased, while increasing on trail making task
Kleinlogel *et al.* [46]	15 M	900 & 1950 MHz PM 217 Hz 1 W/kg	During task	Double	5	No effects
Koivisto *et al.* [58]	24 M, 24 F	902 MHz PM 217 Hz -	Prior and during task	Single	12	Decrease RT in 2 working memory tasks
Koivisto *et al.* [59]	24 M, 24 F	902 MHz PM 217 Hz -	Prior and during task	Single	12	RT increased in 1 task
Krause *et al.* [40]	12 M, 12 F	902 MHz PM 217 Hz 0.878 mW/kg	During task	Double	1	Increase in number of errors
Krause *et al.* [8]	36 M	902 MHz CW & PM 217 Hz 1.1 W/kg	During task,	Double	2	No effects
Lass *et al.* [62]	63 M, 37 F	450 MHz PM 7 Hz	During task	Single	3	Less complicated task decrease in errors, 2 other tasks an increase in error variance
Lee *et al.* [65]	78 -	1900 MHz PM	Prior to task	Single	2	No effect on trail making task, decrease RT in attention task and increase in performance
Maier *et al.* [67]	11 -	902 MHz PM 217 Hz	During task	-	1	Decrease in performance
Papageorgiou *et al.* [51]	9 M, 10 F	900 MHz -	During task	-	1	No effects
Preece *et al.* [56]	18 M, 18 F	915 MHz CW & PM 217 Hz -	During task	-	10	Decrease in RT in choice reaction task during exposure (effect larger for CW signal than PM signal)
Regel *et al.* [73]	15 M	900 MHz PM 217 Hz 0.1 W/kg, 5 W/kg	Prior to task	Double	3	Speed decreased in 1 task with increasing field intensity
Russo *et al.* [74]	69 M, 99 F	888 MHz CW & PM 217 Hz 1.4 W/kg	During task	Double	4	No effects
Schmid *et al.* [68]	29 M, 29 F	1970 MHz 0.84 W/kg	During task	Double	4	No effects
Smythe *et al.* [64]	33 M, 29 F	1800 MHz 0.79 W/kg	Prior to task	-	2	No effect on short-term recall task, decrease in errors in male subjects in long-term recall task

* M – males, F – females, - gender not mentioned ** exposure parameters given are frequency (MHz), pulse modulation (PM) frequency and estimated average field intensity W/kg (SAR)

Most studies investigating RF-EMF effects in human volunteers have a relatively limited number of participants. Russo *et al.* [74] recruited 168 participants to assess attention measures during exposure to a 888MHz PM and CW signal. No significant changes in performance on attention tasks were observed for both the PM and CW signal. Haarala *et al.* [(72)] also exposed the participants to a PM and CW signal (902MHz), and no effects of RF-EMF were found on RT or accuracy of the answers during the assessment of cognitive function. Similar, Krause *et al.* [(8)] observed no effect of a PM 902MHz mobile phone signal performance during a visual working memory task. Regel *et al.* [(34)] used different field intensities (SAR) in their study. Participants were exposed to a 900MHz mobile phone, emitting RF-EMF with either 0.2W/kg or 5W/kg. RT was observed to increase with increasing field intensity, but this effect was only significant in one of the three tasks (RT increment was observed as trend in the other tasks). On accuracy of performance, no effects of RF-EMF exposure were found.

As most studies investigated effects of a single RF-EMF exposure event, Curcio *et al.* [(71)] included multiple exposure rounds to assess a potential cumulative exposure effect. Study objects were exposed to 3 rounds of 15 minute RF-EMF exposure (902.4MHz, PM), and after each round an acoustic simple reaction time task and sequential finger tapping task were administered. A non-significant trend in decreasing reaction times was observed, but in none of the rounds an effect of RF-EMF exposure on human psychomotor performance was found.

Recently, one meta-analysis was published on RF-EMF exposure and neurobehavioral performance [(75)]. Barth *et al.* included 10 blinded (single and double) controlled trials, making use of GSM 900MHz exposure, in young healthy adults. Different performance measures or tasks were included (n=29). The meta-analysis indicated that cognitive performance (subtraction task) was mildly facilitated by EMF exposure. However, this effect in only seen for RT, not for the accuracy outcomes. Inconsistent results were found for the short term memory measures. In one of the four N-back tasks, which assesses short-term memory, target RT increased and the amount of error increased. In conclusion this meta-analysis indicates small, but significant, pooled effects of RF-EMF exposure on attention and working memory, without a uniform direction.

4.2.1 Studies including both brain activity and neurobehavioral measures

Of the previously described studies, some assessed both brain activity and neurobehavioral performance in the same group of participants. These studies are summarized in table 5. Comparison of the findings on brain activity and neurobehavioral performance indicates that, although an alteration of brain activity might be observed, this is not necessarily associated with similar positive findings in the administered neurobehavioral performance tasks (RT and accuracy).

Table 5. Overview of studies investigating the effect of RF-EMF on both brain activity and neurobehavioral performance in the same individuals.

Study	Results brain activity	Results neurobehavioral outcomes
Croft *et al.* [20]	Increase alpha activity, decrease in delta band	No effects
Freude *et al.* [36]	Decrease slow brain potentials	No effects
Freude *et al.* [37]	Decrease slow brain potentials in visual monitoring task (no effect on other 2 tasks)	No effects
Hamblin *et al.* [42]	Auditory EP amplitude and timing altered	Increase RT
Hamblin *et al.* [43]	No effects	No effects
Hinrichs *et al.* [44]	Alteration EP timing	No effects
Kleinlogel *et al.* [46]	No effects	No effects
Krause *et al.* [39]	Increase theta and alpha band power	No effects
Krause *et al.* [40]	No effects	Increase in number of errors
Krause *et al.* [8]	Difference alpha response during auditory memory task between PM and CW signal (not with sham)	No effects
Papageorgiou *et al.* [51]	Total EEG energy decrease in males, increase in females.	No effects

4.4 RF exposure and neurophysiological effects in children

4.4.1 Theoretical background

A review by Leitgreb *et al.* [76] summarizes the arguments provided by scientist arguing the potential higher susceptibility of children to RF-EMF exposure. As children are still in development, their immune and regulatory system is not fully developed yet. Also their cells are dividing at a higher rate than adults, which increases the probability of vulnerable cell cycle phases being present during exposure. This latter argument is of particular interest when considering potential genotoxic effect of (cumulative long-term) RF-EMF exposure. Also the RF-EMF exposure dose (SAR) received by children during mobile phone use is potentially higher than those of adults. The skull of children is still growing and therefore the brain might be more exposed because of a smaller skull thickness, a more flexible ear, allowing a closer position of the phone to the head. Another argument given is the smaller head size of children relative to the RF-EMF penetration depth. Therefore the children's brain may be exposed to a larger extent or depth. A recent study by Wiart *et al.* [2] indicated that the SAR levels inside children phantoms are indeed higher than those in adult phantoms, supporting the previously described arguments. Other researches mention a higher absorption ability of children's brain tissue because of the unfavorable influence of its higher water content. It has been argued that different head shapes and thinner skulls may make them more susceptible to RF-EMF, but besides these structural differences between children and adults, children also have different patterns of mobile phone use. It is a fact that children use mobile phones earlier in life, and thereby accumulate a higher lifetime exposure compared to adults. Furthermore, children might have more unfavorable patterns of mobile phone use (for example no headsets and longer calls).

4.4.2 Children in (experimental) studies

There have been some experimental studies that (also) included children or young adults as participants (table 6). The study by Kramarenko and Tan [21] included both adults and children (12 years old). They observed the induction of abnormal slow waves in the EEG of persons awake, with a difference between adults and children. In the children, the observed slow waves appeared earlier (latency 10-20 seconds) than in adults and their frequency was lower (1.0-2.5Hz), with longer duration and shorter intervals. Based on this finding the authors concluded that children may be more vulnerable to the adverse health effects of mobile phones than adults.

Preece *et al.* [77] repeated an earlier study performed in adults [56], with children between 10 and 12 years old. The children were exposed to a mobile phone (900MHz, PM) for 30 minutes. The RT in children was observed to be slower than the RT observed in an earlier study with adults [56]. Exposure to PM RF-EMF was associated with a slight decrease in RT, but this effect was not significant after Bonferroni correction. No effects were found of performance. This study in children did not replicate the earlier findings in adults that exposure to RF-EMF was associated with a reduction in reaction time [56], but in that study the effect was observed with a CW signal. Similar null-findings were reported by Haarala *et al.* [78]. The children were exposed to both sham and EMF (902 MHz, PM), during the performance of 8 cognitive tasks for 50 minutes. No effect of RF-EMF exposure on the cognitive function of children (10-14 years) was observed. While using children in the same age range, Krause *et al.* [79] found that auditory verbal memory tasks were affected in children during exposure to a 902 MHz mobile phone. EMF was reported to increase ERD/ERS differences during both recoding and recognition.

Table 6. Studies investigating the effects of RF-EMF on brain activity and neurobehavioral performance in children.

Study	Study subjects (n)*	Exposure **	Duration	Blinding	Measure	Main outcomes
Kramarenko *et al.* [21]	10 M (adults), 10 M (12 yr)	900 MHz PM 217 Hz -	During a call	-	EEG	Abnormal slow waves during exposure, different between adults and children
Preece *et al.* [77]	18 (± 11yr)	902 MHz PM 217 Hz 0.28 W/kg	During tasks	-	NBTB 16 tasks	No effects (tendency of shorter RT during exposure)
Haarala *et al.* [78]	16 M, 16 F (± 12 yr)	902 MHz PM 217 Hz 1.44 W/kg	During tasks	Double	NBTB 8 tasks	No effects
Krause *et al.* [79]	6 M, 9 F (10-14 yr)	902 MHz PM 217 Hz 1.40 W/kg	During tasks	Double	EEG	ERD/ERS response altered in theta band during exposure

* M – males, F – females, ** exposure parameters given are frequency (MHz), pulse modulation (PM) frequency and estimated average field intensity W/kg (SAR)

5. Discussion

As mobile phone use is a rapidly increasing technology affecting almost everyone in today's western world society. Mobile phone exposure is localized at the head of an individual, and the RF-EMF emitted by the phone is absorbed through the skull to some extent, and the brain is thereby exposed to this radiation. Potential effects of RF-EMF on the brain are therefore of specific interest. This thesis focused on potential effects of RF-EMF from mobile phone signals on human brain activity and neurobehavioral performance.

5.1 Brain activity

The studies that investigated the effect of exposure to RF-EMF (mainly GSM 900 MHz) on *resting EEG*, predominantly report a significant increase in alpha band EEG power [16, 19, 20, 22, 23]. To a lesser extent, modification of the beta band is reported [16, 22]. For the delta band, both an increase [21] and decrease [20] in EEG power were reported. A smaller number of studies finds no effects of RF-EMF on resting EEG brain activity [17, 24]. Roschke *et al.* [17] used a similar signal and exposure protocol as a previous positive study [16], but found no effect of RF-EMF. Duration of exposure was shortened from 15 minutes to 3.5 minutes in the second study, which could explain this null-finding.

Hinrikus *et al.* [25, 26, 80] performed studies with a signal of a different frequency, 450 MHz, which was pulse modulated at different frequencies. Significant alterations of both the beta and alpha band were observed in the resting EEG and this effect depended on the pulse modulation used. A similar observation was reported by Huber *et al*. [19], who found no effect of a CW-signal, while the PM signal significantly increased spectral alpha band power. Pulse modulation of the signal should therefore be considered an important element of RF-EMF exposure. Another finding from these studies that should be kept in mind is the timing of exposure relative to the EEG. Some studies have exposed participants prior to the EEG recording [16, 19, 23], while in other studies RF-EMF was on during the EEG recording [20, 23]. All these studies observed an effect of RF-EMF on brain activity, implicating that RF-EMF has an delayed or 'wash-out' effect. Curcio *et a.* [23] compared resting EEG taken after and during RF-EMF exposure, and found that the observed effects were larger when RF-EMF exposure occurred on during recording. This finding can either be caused by a delayed RF-EMF effect, with less strength than acute RF-EMF exposure, but also an interaction between RF-EMF and the EEG recoding devices is a possibility [81].

Many of the studies addressing potential effects of RF-EMF exposure on the sleep EEG, also report an increase in alpha power in the NREM sleep [30-34, 82]. One study reported a similar increase in alpha power during the REM sleep [27]. For the other spectral bands, significant increment of spectral power on the sigma band was reported during NREM sleep [30, 31, 82]. Two attempts [28, 29] were made to replicate the first positive finding [27]. In both studies, no effects on the sleep EEG could be detected, even through the latest study [29] used the maximum SAR level allowed (50 W/kg). Small changes in study design had been made, e.g. a different antenna and the location of the source, which were mentioned as potential explanations for the null-findings. That such a high SAR produces a null-finding is in contrast to the study by Regel *et al.* [34] were two RF-EMF signals were used, one with a low SAR 0.2 W/kg and one with a higher SAR of 5W/kg. A dose dependent increase in alpha range frequency power was observed, indicating that increased SAR or field intensity enhances the RF-EMF effect on the brain response. The exposure schemes used, differed between the sleep studies. Whereas Borbely *et al.* [30] used an intermittent whole night exposure, other studies exposed the participants prior to sleep onset [31, 32] or employed both exposure methods in different experiments [33]. In these latter studies effects of RF-EMF exposure were found during sleep, while exposure took place prior to sleep. This indicates that RF-EMF may have a delayed effect, which could be problematic considering often used cross-over exposure patterns.

In most of these studies, sleep architecture and other sleep variables were also reported. These results are less consistent than those of the sleep EEG. Three studies out of 10 found no effect on conventional sleep parameters [28, 29, 34]. Two out of 10 studies [30, 33] reported reduced WASO, indicating a sleep promoting effect of RF-EMF. However, in the study by Huber *et al.* [33] this effect was only observed in the group exposed during the whole night-time sleep episode, contradicting a potential delayed effects of RF-EMF on sleep architecture. Furthermore, earlier onset of REM sleep was reported [32], while in contrast two other studies [9, 27] found an inhibitory effect of RF-EMF on sleep. Hung *et al.* [9] sleep was delayed in individuals exposed to the “talk-mode” (signal PM 8, 217Hz) of the mobile phone compared to the “listen-mode” (signal PM 2, 8, 217 Hz) and the sham exposure condition. Thereby this study suggests that small differences in pulse modulation of the RF-EMF signal might have a large impact on study results. That pulse modulation is important was also shown by Huber *et al.* [19].

For the EEG recordings during cognitive processing rather inconsistent results have been reported. Due to the large number of different tasks employed in these studies, comparability is difficult. Some studies report RF-EMF induced changes in alpha frequency during cognitive processing [20, 35, 38, 39, 52], but also changes in beta [48, 49], delta [20, 36, 37] and theta band [38, 39] Significant effects of RF-EMF on other cognitive metrics (N100 and P300) were also reported [42, 44, 54]. A number of studies report null-findings [8, 40, 41, 46, 50, 53, 83]. Noteworthy is the fact that the two null-findings of Krause *et al.* [8, 40] were replication studies of earlier positive studies [38, 39]. The main change was the adoption of a double blind study design in the two later studies, implicating that their earlier findings might be caused by problems in study design. A similar effect was observed for Hamblin *et al.* The first study [42] reported a positive effect or RF-EMF exposure on P300, in a single blind design. The second study [43] adopted a double blind design with a larger sample size and the earlier findings could not be replicated.

Another finding reported in multiple studies, is a potential effect modification by gender on RF-EMF exposure. Four studies [45, 48, 49, 51] report on different gender-related responses to RF-EMF exposure Overall, baseline EEG power is higher in males than in females, but during exposure to RF-EMF, EEG power decreases in males and increases in females. However, a large number of other studies also includes both male and female participants, and do not report a gender related differences. As for the previously mentioned studies [45, 48, 49, 51] no information on blinding was available, the reliability of these observed gender-related difference is difficult to determine. Whether responses to RF-EMF in males and females are indeed different, should be further investigated.

Overall, the reviewed publications investigating possible effects of RF-EMF exposure on brain activity suggests that brief, acute exposures of the head to mobile phone like signals (mainly 900MHz) can induce measurable changes in human brain electrical activity. The most consistent outcome during rest, sleep and cognitive processing is an increase in alpha frequency power during and after RF-EMF exposure. For other frequency bands and sleep variables results are less consistent.

5.2 Neurobehavioral performance

The effect of RF-EMF on various performance measures, predominantly neurophysiological tasks of working memory and attention, is also inconsistent between studies. A large number of studies finds no effect of RF-EMF on RT or performance in tasks [8, 20, 36, 37, 46, 51, 55, 61, 68, 69, 71, 72, 74, 77, 83]. Another large part of the studies in this field report a facilitating effect of RF-EMF on cognitive performance on different tasks by either a decrease in RT [42, 56, 58, 59, 65, 66] or an increase in performance [56, 63-65]. However, also (fewer) studies reporting decrease RT or performance were found [40, 57, 67, 70], and one study reported an increase in error variance in relation to RF-EMF exposure [62]. It is difficult to draw any conclusion from these studies as many of them assess different cognitive domains or include different performance tasks for a certain domain. In most studies the significant effect reported is only observed in one of the many tasks administered. The meta-analysis by Barth *et al.* pooled data from 10 studies and found a small, but significant, pooled effect of RF-EMF exposure on the cognitive domains attention and working memory.

Interestingly, the same issue of study blinding came up in these studies. Where the single-blinded studies by Koivisto *et al.* [58, 59] did found effects of RF-EMF on RT, the double-blinded replication studies by Haarala *et al.* [61, 72] found no such effect with a larger sample size.

In two studies [63, 66] effects were observed to be larger when study objects were exposed to RF-EMF prior to the performance task. These results suggest that there might be a certain latency between RF-EMF exposure and neurobehavioral outcomes.

5.3 Long-term effects

The studies described in this literature review were predominantly experimental studies assessing the acute effects of RF-EMF exposure on brain activity and performance measures. Curcio *et al.* [(71)] tried to identify a potential cumulative effect of repeated RF-EMF exposure by exposing subjects to several blocks of 15 min RF-EMF, but did not find any effects of RF-EMF on the tasks administered after each exposure block. Besset *et al.* [(69)] exposed their treatment group to RF-EMF (900MHz) for 120 min per day, for multiple days, and administered neurobehavioral tasks the day after exposure took place. No effects were found however, and the authors concluded that the longer time between exposure to the mobile phone and the subsequent testing may have allowed for recovery of function.

No other studies addressing potential cumulative or long-term effects of RF-EMF exposure on brain activity and neurobehavioral performance were identified. In an experimental setting cumulative exposure will also be difficult to asses, as time is often limited. To address a true cumulative exposure other types of (observational) study designs would be more feasible. It is unknown whether RF-EMF might have a cumulative effect on the longer term, and especially for children, who will have high cumulative lifetime exposures, this is a very relevant issue.

5.4 Children

As summarized by Leitgeb *et al.* [(76)], there is a list of arguments why children could be a potential more susceptible group to RF-EMF exposure than adults. Among the experimental studies included the literature review, four studies included children as their participants. Two studies investigating the effect of RF-EMF GSM signals on brain activity did found some effects in children. Kramarenko *et al.* [(21)] found a difference in the induced slow waves between children and adults, with the effect being earlier visible in children compared to adults with the same experimental treatment. However, this study was criticized for not using any form of blinded study design or randomization [(12)]. Furthermore, Krause *et al.* found a significant difference in ERD/ERS after RF-EMF exposure. No effects of RF-EMF on neurobehavioral performance of children were observed [(77, 78)].

In conclusion, the amount and quality of the studies addressing effects of acute RF-EMF exposure on brain activity and cognitive function in children are limited. There might be small alterations of brain activity in children following RF-EMF exposure, but similar to the adult studies, no effects on neurobehavioral performance are observed. However, if RF-EMF would have long-term cumulative effects, children need to be considered to be at relatively higher risk than adults due to their longer lifetime cumulative exposure.

5.5 Methodological issues in RF-EMF studies

One possible explanation for the variation in reported results concerning RF-EMF exposure may well be the lack of standardized and validated outcome measures (e.g. measurement of brain waves) and the sensitivity of cognitive tasks to assess effects of RF-EMF, as well as to the different experimental protocols and highly variable EMF parameters. With regard to the methodologies used in RF-EMF research, limited validation has taken place (81). The EEG, which is the most used measurement device, is a method susceptible to artifacts. Little changes in eye movement or other small movements can cause these artifacts in the measurement as well as RF-EMF in interacting with the recoding electrodes. With regard to the alpha rhythm, there is discussion on the validity of this measure. It has been suggested that alpha rhythm has moderate to bad scoring agreement and also that about 10-20% of the population has little or no alpha rhythm (81). This could result in failure to measure alpha frequency in substantial portion of the study participants. As alpha rhythm is often used to determine sleep onset (9), this could also have implication for findings on sleep architecture.

With regard to exposure parameters, differences are observed in exposure source location, distance to the head, pulse modulation and field intensity of the signal. Exposure side is considered to be of minor importance as no differences in RF-EMF related effects are reported in relation to the side of exposure (33, 74). Pulse modulation on the other hand, has been reported as important (19, 80). However, as indicated by Hung *et al.* (9) in their recent review, studies use very different modulation schemes, while referring to the same kind of exposure, e.g. a 900 MHz mobile phone signal.

Furthermore, in some studies the number of participants is relatively small. A substantial amount of participants is needed to compensate for potential intra- and inter-individual variability in responsiveness to RF-EMF or factors influencing cognitive performance (e.g. motivation, distraction, boredom etc.). As males and females might have a differential response to RF-EMF exposure, equally sized groups of both sexes are needed to evaluate such an effect. Also differences in blinding design might have an influence on study outcome. Many of the early RF-EMF studies reporting positive findings had a single blinded design. When repeating previous positive studies, with an enhanced double blinded design and increased number of participants, Hamblin *et al.* (43), Haarala *et al.* (61, 72) and Krause *et al.* (8) did not find outcomes consistent to their previous studies.

As also discussed by Cook *et al.* in their review (84), the timing of the RF-EMF exposure is also an important issue. There are studies indicating a delayed effect of RF- EMF exposure (19, 23, 33, 42, 44, 63) on the outcomes of interest. When delayed effects are present, this could be problematic with the cross-over designs, where such a “wash-out” effect is not taken into account and sham and exposure conditions closely follow each other.

5.6 Practical implications

Considering the reported effects of RF-EMF on brain activity and neurobehavioral outcomes, the conclusion can be drawn that a significant number of studies report an RF-EMF related alteration of the alpha frequency band on the EEG during rest, sleep and cognitive processing during and after exposure to GSM like signals (900 MHz). The possible clinical significance of the higher amount of alpha activity after or during RF-EMF exposure is largely unknown. Different results are published concerning associations between alpha activity and functional processes. The alpha rhythm is associated with a cortical de-activation, cognitive inhibition and visual relaxation and alpha power at 10 Hz is considered to reflect the transition from waking to sleep [(9)]. However this band is also be recoded during activities and tasks, implying that it is a rather unspecific response of the CNS [(12)]. Considering the lack of information on alpha band function and the absence of evidence for potential mechanisms underlying RF-EMF induced effects, it is difficult to interpret study outcomes and assign a clinical significance to the observed alterations in this band induced by RF-EMF exposure.

The Dutch health council [(85)] reviewed literature available till 2002 and stated that the magnitude of changes found in brain activity patterns induced by EMF are comparable to brain activity effects found for caffeine use and regular hormonal shifts. It would be incorrect to state that mobile phone use has no effect on everyday functioning, as for example caffeine does influence behavior, but again the clinical significance is questionable. An important observation is that the studies investigating behavioral performance measures show less and more inconsistent results. The majority of studies addressing both brain activity and neurobehavioral performance find no effects regarding the latter (table 5). This indicates that either these alterations of brain activity are not related to the studied behavioral outcomes, subtle changes in brain activity may not lead to changes in behavior or the used neurobehavioral performance measures might not be sensitive enough to record small changes induced. The effects observed from the pooled meta-analysis [(75)] are small and lack uniform direction, and as stated by the authors: “The effects seem to be so small that implications for human performance in everyday life can be practically ruled out”.

Taking into account that RF-EMF induced changes in brain activity in the same order of magnitude as changes induced by exposure to caffeine or hormonal shifts, and the absence of evidence for RF-EMF to influence behavioral performance measures, it can be concluded that acute exposure to RF-EMF signals is unlikely to affect human every day functioning.

With regard to children and RF-EMF exposure to the head due to mobile phone use, the data to date is too limited to draw conclusions. They remain a controversial combination and governments need to determine whether precautionary measures should be taken. Several national governments attempt to discourage mobile phone use by children. However, the Dutch Health Council concluded that there is no convincing scientific data to assume children to be more susceptible to RF-EMF and therefore they do not recommend limiting the use of mobile phones by children [(86)].

6. Conclusion

Consistent small changes in alpha frequency spectral power are observed on EEG in rest, sleep and during cognitive processing, during and after exposure to RF-EMF resembling GSM phone signals. The clinical significance of these small changes in brain activity is currently not well known, and it is suggested that brain activity can be altered in a similar extent by caffeine or hormonal shifts. Furthermore, these alterations of brain activity are not accompanied by effects of RF-EMF exposure on neurobehavioral performance. Taking this information into account, it can be concluded that acute exposure of the head to RF-EMF, resembling GSM phone signals, is unlikely to impair (or improve) human cognitive functioning.

The number and quality of studies among children is at present too limited to conclude that children would indeed be a more susceptible sub-group of mobile phone users. However, as it is unknown whether RF-EMF might have a cumulative effect on brain activity or neurobehavioral performance on the long term, children, who will have high cumulative lifetime exposures, should be monitored closely.

7. Future research

Future EMF research should focus on potential long-term or cumulative effects of RF-EMF, especially with regard to children, and also take in account other sources of RF (and ELF) in the environment to produce a reasonable cumulative exposure estimate. Most of the experimental studies investigated RF-EMF from GSM signals (900MHz), and to date little attention has been given to the frequencies used in UMTS signals, while many phones currently used make use of this latter technology.

For the experimental studies standardized measurement techniques and exposure protocols are needed, to provide the opportunity pool data to assess potential effects of RF-EMF within a larger sample. Attention should be given to improving study design. All studies should be double blinded, as it is unknown to what extent knowledge on the study and exposure influences the participant's brain activity and response in neurobehavioral tasks. Furthermore, the potential influence of a delayed- and order-effect related to RF-EMF exposure should be further investigated and designs should be balanced in that respect (randomized counterbalanced design). To address individual variation in response to RF-EMF, it would also be helpful to include repeated measurements per participants and a positive control in these experimental studies. As caffeine has a well described effect on brain activity and neurobehavioral performance, this might be explored as a potential positive control in RF-EMF experiments. Furthermore, observational studies suggest that there is a cognitive training effect related to mobile phone use. Reaction time and accuracy seem to be related to the extent of mobile phone use [87, 88], and although it is, as yet assumed, unlikely that RF-EMF exposure would play a role in this training effect, mobile phone use of participants should be assessed in each experimental study.

Finally, more insight in potential mechanisms of interaction between RF-EMF and the brain would be helpful in improving future study design, as it currently not well known which endpoints are most relevant to study in relation to RF-EMF exposure.

References

1. Centraal Bureau voor de Statistiek. *De Digitale Economie 2008.* Den Haag: Centraal Bureau voor de Statistiek; 2008.

2. Wiart J, Hadjem A, Wong MF, Bloch I. Analysis of RF exposure in the head tissues of children and adults. *Physics in Medicine and Biology.* 2008;53:3681-3695.

3. Divan HA, Kheifets L, Obel C, Olsen J. Prenatal and postnatal exposure to cell phone use and behavioral problems in children. *Epidemiology.* 2008;19:523-529.

4. Feychting M, Ahlbom A, Kheifets L. EMF and health. 2005:165-189.

5. Schuz J, Ahlbom A. Exposure to electromagnetic fields and the risk of childhood leukaemia: A review. *Radiation Protection Dosimetry.* 2008;132:202-211.

6. Krewski D, Glickman BW, Habash RWY, et al. Recent advances in research on radiofrequency fields and health: 2001-2003. *Journal of Toxicology and Environmental Health - Part B: Critical Reviews.* 2007;10:287-318.

7. Wikipedia. G4 mobile phone technology. 2010.

8. Krause CM, Pesonen M, Bjornberg C, Hamalainen H. Effects of pulsed and continuous wave 902 MHz mobile phone exposure on brain oscillatory activity during cognitive processing. *Bioelectromagnetics.* 2007;28:296-308.

9. Hung CS, Anderson C, Horne JA, McEvoy P. Mobile phone 'talk-mode' signal delays EEG-determined sleep onset. *Neuroscience Letters.* 2007;421:82-86.

10. Phillips JL, Singh NP, Lai H. Electromagnetic fields and DNA damage. *Pathophysiology.* 2009;16:79-88.

11. Friedman J, Kraus S, Hauptman Y, Schiff Y, Seger R. Mechanism of short-term ERK activation by electromagnetic fields at mobile phone frequencies. *Biochemical Journal.* 2007;405:559-568.

12. Valentini E, Curcio G, Moroni F, Ferrara M, De Gennaro L, Bertini M. Neurophysiological effects of mobile phone electromagnetic fields on humans: A comprehensive review. *Bioelectromagnetics.* 2007;28:415-432.

13. Krause CM. Brain oscillations and cognitive processes. 2006.

14. Danker-Hopfe H, Dorn H. Biological effects of electromagnetic fields at mobile phone frequencies on sleep: Current state of knowledge from laboratory studies. *Somnologie.* 2005;9:192-198.

15. Ahlbom A, Bergqvist U, Bernhardt JH, et al. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Physics.* 1998;74:494-521.

16. Reiser H, Dimpfel W, Schober F. The influence of electromagnetic fields on human brain activity. *European journal of medical research.* 1995;1:27-32.

17. Roschke J, Mann K. No Short-Term Effects of Digital Mobile Radio Telephone on the Awake Human Electroencephalogram. *Bioelectromagnetics.* 1997;18:172-176.

18. Hietanen M, Kovala T, Hamalainen H. Human brain activity during exposure to radiofrequency fields emitted by cellular phones. *Scandinavian Journal of Work, Environment and Health.* 2000;26:87-92.

19. Huber R, Treyer V, Borbely AA, et al. Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. *Journal of Sleep Research.* 2002;11:289-295.

20. Croft RJ, Chandler JS, Burgess AP, Barry RJ, Williams JD, Clarke AR. Acute mobile phone operation affects neural function in humans. *Clinical Neurophysiology.* 2002;113:1623-1632.

21. Kramarenko AV, Tan U. Effects of high-frequency electromagnetic fields on human EEG: A brain mapping study. *International Journal of Neuroscience.* 2003;113:1007-1019.

22. D'Costa H, Trueman G, Tang L, et al. Human brain wave activity during exposure to radiofrequency field emissions from mobile phones. *Australasian Physical and Engineering Sciences in Medicine.* 2003;26:162-167.

23. Curcio G, Ferrara M, Moroni F, D'Inzeo G, Bertini M, De Gennaro L. Is the brain influenced by a phone call? An EEG study of resting wakefulness. *Neuroscience Research.* 2005;53:265-270.

24. Kleinlogel H, Dierks T, Koenig T, Lehmann H, Minder A, Berz R. Effects of weak mobile phone - Electromagnetic fields (GSM, UMTS) on well-being and resting EEG. *Bioelectromagnetics.* 2008;29:479-487.

25. Hinrikus H, Bachmann M, Lass J, Karai D, Tuulik V. Effect of low frequency modulated microwave exposure on human EEG: Individual sensitivity. *Bioelectromagnetics.* 2008;29:527-538.

26. Hinrikus H, Bachmann M, Lass J, Tomson R, Tuulik V. Effect of 7, 14 and 21 Hz modulated 450 MHz microwave radiation on human electroencephalographic rhythms. *International Journal of Radiation Biology.* 2008;84:69-79.

27. Mann K, Roschke J. Effects of pulsed high-frequency electromagnetic fields on human sleep. *Neuropsychobiology.* 1996;33:41-47.

28. Wagner P, Roschke J, Mann K, Hiller W, Frank C. Human Sleep under the Influence of Pulsed Radiofrequency Electromagnetic Fields: A Polysomnographic Study Using Standardized Conditions. *Bioelectromagnetics.* 1998;19:199-202.

29. Wagner P, Roschke J, Mann K, et al. Human sleep EEG under the influence of pulsed radio frequency electromagnetic fields: Results from polysomnographies using submaximal high power flux densities. *Neuropsychobiology.* 2000;42:207-212.

30. Borbely AA, Huber R, Graf T, Fuchs B, Gallmann E, Achermann P. Pulsed high-frequency electromagnetic field affects human sleep and sleep electroencephalogram. *Neuroscience Letters.* 1999;275:207-210.

31. Huber R, Graf T, Cote KA, et al. Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG. *NeuroReport.* 2000;11:3321-3325.

32. Loughran SP, Wood AW, Barton JM, Croft RJ, Thompson B, Stough C. The effect of electromagnetic fields emitted by mobile phones on human sleep. *NeuroReport.* 2005;16:1973-1976.

33. Huber R, Schuderer J, Graf T, et al. Radio Frequency Electromagnetic Field Exposure in Humans: Estimation of SAR Distribution in the Brain, Effects on Sleep and Heart Rate. *Bioelectromagnetics.* 2003;24:262-276.

34. Regel SJ, Tinguely G, Schuderer J, et al. Pulsed radio-frequency electromagnetic fields: Dose-dependent effects on sleep, the sleep EEG and cognitive performance. *Journal of Sleep Research.* 2007;16:253-258.

35. Eulitz C, Ullsperger P, Freude G, Elbert T. Mobile phones modulate response patterns of human brain activity. *NeuroReport.* 1998;9:3229-3232.

36. Freude G, Ullsperger P, Eggert S, Ruppe I. Effects of Microwaves Emitted by Cellular Phones on Human Slow Brain Potentials. *Bioelectromagnetics.* 1998;19:384-387.

37. Freude G, Ullsperger P, Eggert S, Ruppe I. Microwaves emitted by cellular telephones affect human slow brain potentials. *European Journal of Applied Physiology and Occupational Physiology.* 2000;81:18-27.

38. Krause CM, Sillanmaki L, Koivisto M, et al. Effects of electromagnetic field emitted by cellular phones on the EEG during a memory task. *NeuroReport.* 2000;11:761-764.

39. Krause CM, Sillanmaki L, Koivisto M, et al. Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. *International Journal of Radiation Biology.* 2000;76:1659-1667.

40. Krause CM, Haarala C, Sillanmaki L, et al. Effects of Electromagnetic Field Emitted by Cellular Phones on the EEG during an Auditory Memory Task: A Double Blind Replication Study. *Bioelectromagnetics.* 2004;25:33-40.

41. Bak M, sliwinska-Kowalska M, Zmyslony M, Dudarewicz A. No effects of acute exposure to the electromagnetic field emitted by mobile phones on brainstem auditory potentials in young volunteers. *International Journal of Occupational Medicine and Environmental Health.* 2003;16:201-208.

42. Hamblin DL, Wood AW, Croft RJ, Stough C. Examining the effects of electromagnetic fields emitted by GSM mobile phones on human event-related potentials and performance during an auditory task. *Clinical Neurophysiology.* 2004;115:171-178.

43. Hamblin DL, Croft RJ, Wood AW, Stough C, Spong J. The sensitivity of human event-related potentials and reaction time to mobile phone emitted electromagnetic fields. *Bioelectromagnetics.* 2006;27:265-273.

44. Hinrichs H, Heinze HJ. Effects of GSM electromagnetic field on the MEG during an encoding-retrieval task. *NeuroReport.* 2004;15:1191-1194.

45. Hountala CD, Maganioti AE, Papageorgiou CC, et al. The spectral power coherence of the EEG under different EMF conditions. *Neuroscience Letters.* 2008;441:188-192.

46. Kleinlogel H, Dierks T, Koenig T, Lehmann H, Minder A, Berz R. Effects of weak mobile phone - Electromagnetic fields (GSM, UMTS) on event related potentials and cognitive functions. *Bioelectromagnetics.* 2008;29:488-497.

47. Maby E, Le Bouquin Jeannes R, Faucon G. Short-term effects of GSM mobiles phones on spectral components of the human electroencephalogram. *Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Conference.* 2006;1:3751-3754.

48. Nanou E, Tsiafakis V, Kapareliotis E, Papageorgiou C, Rabavilas A, Capsalis C. Influence of the interaction of a 900 MHz signal with gender on EEG energy:

Experimental study on the influence of 900 MHz radiation on EEG. *Environmentalist.* 2005;25:173-179.

49. Nanou E, Hountala C, Maganioti A, et al. Influence of a 1,800 MHz electromagnetic field on the EEG energy. *Environmentalist.* 2009;29:205-209.

50. Oysu C, Topak M, Celik O, Yilmaz HB, Sahin AA. Effects of the acute exposure to the electromagnetic field of mobile phones on human auditory brainstem responses. *European Archives of Oto-Rhino-Laryngology.* 2005;262:839-843.

51. Papageorgiou CC, Nanou ED, Tsiafakis VG, Capsalis CN, Rabavilas AD. Gender related differences on the EEG during a simulated mobile phone signal. *NeuroReport.* 2004;15:2557-2560.

52. Vecchio F, Babiloni C, Ferreri F, et al. Mobile phone emission modulates interhemispheric functional coupling of EEG alpha rhythms. *European Journal of Neuroscience.* 2007;25:1908-1913.

53. Yuasa K, Arai N, Okabe S, et al. Effects of thirty minutes mobile phone use on the human sensory cortex. *Clinical Neurophysiology.* 2006;117:900-905.

54. Maby E, Le Bouquin Jeannes R, Lingeois-Chauvel C, Gourevitch B, Faucon G. Analysis of auditory evoked potential parameters in the presence of radiofrequency fields using a support vector machines method. *Medical and Biological Engineering and Computing.* 2004;42:562-568.

55. Hladky A, Musil J, Roth Z, Urban P, Blazkova V. Acute effects of using a mobile phone on CNS functions. *Central European Journal of Public Health.* 1999;7:165-167.

56. Preece AW, Iwi G, vies-Smith A, et al. Effect of a 915-MHz simulated mobile phone signal on cognitive function in man. *International Journal of Radiation Biology.* 1999;75:447-456.

57. Keetley V, Wood AW, Spong J, Stough C. Neuropsychological sequelae of digital mobile phone exposure in humans. *Neuropsychologia.* 2006;44:1843-1848.

58. Koivisto M, Krause CM, Revonsuo A, Laine M, Hamalainen H. The effects of electromagnetic field emitted by GSM phones on working memory. *NeuroReport.* 2000;11:1641-1643.

59. Koivisto M, Revonsuo A, Krause C, et al. Effects of 902 MHz electromagnetic field emitted by cellular telephones on response times in humans. *NeuroReport.* 2000;11:413-415.

60. Haarala C, Bjornberg L, Ek M, et al. Effect of a 902 MHz Electromagnetic Field Emitted by Mobile Phones on Human Cognitive Function: A Replication Study. *Bioelectromagnetics.* 2003;24:283-288.

61. Haarala C, Ek M, Bjornberg L, et al. 902 MHz mobile phone does not affect short term memory in humans. *Bioelectromagnetics.* 2004;25:452-456.

62. Lass J, Tuulik V, Ferenets R, Riisalo R, Hinrikus H. Effects of 7 Hz-modulated 450 MHz electromagnetic radiation on human performance in visual memory tasks. *International Journal of Radiation Biology.* 2002;78:937-944.

63. Edelstyn N, Oldershaw A. The acute effects of exposure to the electromagnetic field emitted by mobile phones on human attention. *NeuroReport.* 2002;13:119-121.

64. Smythe JW, Costall B. Mobile phone use facilitates memory in male, but not female, subjects. *NeuroReport.* 2003;14:243-246.

65. Lee TMC, Lam PK, Yee LTS, Chan CCH. The effect of the duration of exposure to the electromagnetic field emitted by mobile phones on human attention. *NeuroReport.* 2003;14:1361-1364.

66. Curcio G, Ferrara M, De Gennaro L, Cristiani R, D'Inzeo G, Bertini M. Time-course of electromagnetic field effects on human performance and tympanic temperature. *NeuroReport.* 2004;15:161-164.

67. Maier R, Greter SE, Maier H. Effects of pulsed electromagnetic fields on cognitive processes - A pilot study on pulsed field interference with cognitive regeneration. *Acta Neurologica Scandinavica.* 2004;110:46-52.

68. Schmid G, Sauter C, Stepansky R, Lobentanz IS, Zeitlhofer J. No influence on selected parameters of human visual perception of 1970 MHz UMTS-like exposure. *Bioelectromagnetics.* 2005;26:243-250.

69. Besset A, Espa F, Dauvilliers Y, Billiard M, De Seze R. No effect on cognitive function from daily mobile phone use. *Bioelectromagnetics.* 2005;26:102-108.

70. Eliyahu I, Luria R, Hareuveny R, Margaliot M, Meiran N, Shani G. Effects of radiofrequency radiation emitted by cellular telephones on the cognitive functions of humans. *Bioelectromagnetics.* 2006;27:119-126.

71. Curcio G, Valentini E, Moroni F, Ferrara M, De Gennaro L, Bertini M. Psychomotor performance is not influenced by brief repeated exposures to mobile phones. *Bioelectromagnetics.* 2008;29:237-241.

72. Haarala C, Takuo F, Rintee T, et al. Pulsed and continuous wave mobile phone exposure over left versus right hemisphere: Effects on human cognitive function. *Bioelectromagnetics.* 2007;28:289-295.

73. Regel SJ, Gottselig JM, Schuderer J, et al. Pulsed radio frequency radiation affects cognitive performance and the waking electroencephalogram. *NeuroReport.* 2007;18:803-807.

74. Russo R, Fox E, Cinel C, et al. Does acute exposure to mobile phones affect human attention? *Bioelectromagnetics.* 2006;27:215-220.

75. Barth A, Winker R, Ponocny-Seliger E, et al. A meta-analysis for neurobehavioural effects due to electromagnetic field exposure emitted by GSM mobile phones. *Occupational and Environmental Medicine.* 2008;65:342-346.

76. Leitgeb N. Mobile phones: Are children at higher risk? *Wiener Medizinische Wochenschrift.* 2008;158:36-41.

77. Preece AW, Goodfellow S, Wright MG, et al. Effect of 902 MHz Mobile Phone Transmission on Cognitive Function in Children. *Bioelectromagnetics.* 2005;26.

78. Haarala C, Bergman M, Laine M, Revonsuo A, Koivisto M, Hamalainen H. Electromagnetic field emitted by 902 MHz mobile phones shows no effects on children's cognitive function. *Bioelectromagnetics.* 2005;26.

79. Krause CM, Bjornberg C, Pesonen M, et al. Mobile phone effects on children's event-related oscillatory EEG during an auditory memory task. *International Journal of Radiation Biology.* 2006;82:443-450.

80. Hinrikus H, Bachmann M, Lass J, Tuulik V. Effect of modulated at different low frequencies microwave radiation on human EEG. *Environmentalist.* 2009;29:215-219.

81. Johnston S. Sleep disorders, EEG-changes, altered cognitive functions - Is there a Connection with the Exposure to Mobile Communication RF Fields? 2009.

82. Gailus T, Korotkovskaya TI, Lebedeva NN, Sulimov AV, Sulimova OP. Investigation of brain potentials in sleeping humans exposed to the electromagnetic field of mobile phones. *Critical Reviews in Biomedical Engineering.* 2001;29:125-133.

83. Hinrichs H, Heinze HJ, Rotte M. Human sleep under the influence of a GSM 1800 electromagnetic far field. *Somnologie.* 2005;9:185-191.

84. Cook CM, Saucier DM, Thomas AW, Prato FS. Exposure to ELF magnetic and ELF-modulated radiofrequency fields: The time course of physiological and cognitive effects observed in recent studies (2001-2005). *Bioelectromagnetics.* 2006;27:613-627.

85. Gezondheidsraad. Mobiele telefoons, een gezondheidskundige analyse. 2002.

86. Van Rongen E, Roubos EW, Van Aernsbergen LM, et al. Mobile Phones and Children: Is Precaution Warranted? *Bioelectromagnetics.* 2004;25:142-144.

87. Arns M, Van Luijtelaar G, Sumich A, Hamilton R, Gordon E. Electroencephalographic, personality, and executive function measures associated with frequent mobile phone use. *International Journal of Neuroscience.* 2007;117:1341-1360.

88. Abramson MJ, Benke GP, Dimitriadis C, et al. Mobile telephone use is associated with changes in cognitive function in young adolescents. 2009.