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Jasmina Wallace, Brahim Selmaoui

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Jasmina Wallace[1,2] and Brahim Selmaoui[1,2]

[1]*Experimental Toxicology Unit, National Institute of Industrial Environment and Risks (INERIS), Verneuil-en-Halatte, France*

[2]*PériTox Laboratory, UMR-I-01, Faculty of Medicine, University of Picardy Jules Verne, Amiens, France*

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Corresponding author: Brahim Selmaoui,
INERIS, Parc Technologique Alata BP 2, 60550, Verneuil-en-Halatte, France
e-mail: brahim.selmaoui@ineris.fr
Tel. +33 44 61 82 68 / Fax +33 44 55 66 99

Abstract

In response to the exponential increase in mobile phone use and the resulting increase in exposure to radiofrequency electromagnetic fields (RF-EMF), there have been several studies to investigate via electroencephalography (EEG) whether RF-EMF exposure affects brain activity. Data in the literature have shown that exposure to radiofrequency signals modifies the waking EEG with the main effect on the alpha band frequency (8–13 Hz). However, some studies have reported an increase in alpha band power, while others have shown a decrease, and other studies showed no effect on EEG power. Given that changes in the alpha amplitude are associated with attention and some cognitive aspects of human behavior, researchers deemed necessary to look whether alpha rhythm was modulated under RF-EMF exposure. The present review aims at comparing and discussing the main findings obtained so far regarding RF-EMF effects on alpha rhythm of human waking spontaneous EEG, focusing on differences in protocols between studies, which might explain the observed discrepancies and inconclusive results.

KEYWORDS: radiofrequency electromagnetic field; mobile phones; waking electroencephalography; spontaneous electroencephalography; alpha rhythm

Introduction

New technologies, especially in the area of wireless communication, use electromagnetic fields to transmit information and data for their functioning. The development of these new technologies and their intensive use have inevitably resulted in people's exposure to electromagnetic fields. Mobile phones (MP) are one of the most commonly used tools for wireless communications. Indeed, according to recent statistics from the International Telecommunication Union (ITU), the number of MP subscriptions reached 7.5 billion worldwide in 2016 and an estimate of 7.74 billion worldwide subscriptions in 2017 (ITU, 2018). So, the average annual growth rate in MP subscriptions was about 43% during the last 10 years.

When using MPs to make a phone call, the part of the body most exposed to radiofrequency electromagnetic fields (RF-EMF) is the brain. Concerns have been raised about the effect of RF-EMF as a possible human health risk. Epidemiological studies were conducted to determine whether there was an association between exposure to RF-EMF and brain tumours. The most famous is the Interphone study, which was initiated as an international set of case control studies looking for different types of tumours (Cardis et al., 2011). Globally, the results of this study showed no increase in the risk of glioma or meningioma from the use of mobile phones, however, the authors suggested an increased risk of glioma at the highest exposure levels among long-term users. They also concluded that biases and uncertainty prevented a causal interpretation. Based on this and other studies, the International Agency for Research on Cancer (IARC) classified radiofrequency electromagnetic fields as possibly carcinogenic to humans (IARC, 2011).

A number of generations have been developed for mobile phone communications, from the first generation (1G) up to the fifth (5G). Each of these wireless systems acts with different RF-EMF bands and information coding technologies. 1G analogue-based systems, such as the Nordic Mobile Telephone (NMT) at 450 or 900 MHz, used a modulated frequency and continuous signal. Nowadays, the vast majority of 2G systems around the world is still the Global System for Mobile Communication (GSM) (GSMA, 2018), which typically works at 900 MHz with a frequency pulse-modulated signal, emitting 577 µs pulses every 4.6 ms repeated at a rate of 217 Hz. Additional GSM frequency bands are at 450 MHz and at 1800 MHz. The 1800 MHz band is also known as the Personal Communication Network (PCN). A 3G digital system is the Universal Mobile Telecommunications System (UMTS) network, which operates mainly at 2100 MHz range in downlink and at 1950 MHz range in uplink, and which includes the most common system Wideband Code-Division Multiple-Access (WCDMA). 4G has recently been introduced with the Long Term Evolution (LTE), developed as an improvement to the UMTS technology, supporting higher data rates through wider channel bandwidths with a frequency band which operates at 2600 MHz.

Given this great evolution in MP technologies and the large number of MP users, many human studies have focused on the effect of the RF-EMF emitted by MPs (MP-RF) on the physiology of the brain. Electroencephalography (EEG), which represents the spatial summation of current density resulting from synchronized post-synaptic cortical potentials with a millisecond's temporal resolution, has been widely reported in the literature as the electrophysiological non-invasive technique of choice to investigate effects of MP exposure on brain activity in waking state. Following analyses of the EEG spectral power density, the most consistent effect has been observed in the alpha frequency band. However, observed effects correspond either to an enhanced or a decreased power, so results are difficult to interpret. The alpha rhythm has a frequency between 8 and 13 Hz and its amplitude is around 15 to 45 μV (Leeuwen et al., 1967, Cacioppo et al., 2007, Yamada and Meng, 2012). For many decades it was considered a passive and idling state of the brain (Pfurtscheller et al., 1996), but further more recent studies have shown the alpha rhythm corresponds to a pure cognitive signal, with an active role in attention, memory and cognitive processing (Klimesch, 1999, Palva and Palva, 2007, Roux and Uhlhaas, 2014, Minarik et al., 2018; for review see: Başar, 2012, Klimesch, 2012, Bazanova and Vernon, 2014). Its greatest amplitude is localized at the occipito-temporal and parietal regions when eyes are closed during rest waking state (Niedermeyer and da Silva, 2005). Given that this band frequency is associated with attention and cognitive activity, it is deemed necessary to look and understand its modulation under RF-EMF exposure. So, the present review aims to compare and discuss the main findings obtained so far, concerning MP-RF effects on the human waking spontaneous EEG and the alpha band of different types of population, highlighting the main differences in protocols, which might explain the observed discrepancies and inconclusive results.

Literature methodological search and selection

Electronic database (PubMed, MEDLINE, EMF-Portal) were used to carry out the literature search using keywords related to RF-EMF (such as 'radiofrequency', 'RF', 'electromagnetic field', 'EMF', '900 MHz', '1800 MHz'), MP (such as 'mobile phone', 'cellular phone', '2G', '3G, '4G', 'GSM', 'UMTS', 'LTE'), EEG and brain electrophysiological activity (such as 'electroencephalogram', 'EEG', waking electroencephalogram/EEG', 'spontaneous electroencephalogram/EEG', 'electroencephalogram/EEG at rest', 'alpha/α band/rhythm/frequency', '8–12 Hz/8–13 Hz', 'power spectral density', 'cerebral/brain activity/physiology', 'human'). The last update in the literature search was done in December 2018. Firstly, a pre-selection based on the title and abstract allowed to screen the publications in English language which were relevant to the topic of interest. Then, a more detailed review of relevant articles was performed, based on full text analysis, and selecting the studies with the following inclusion criteria:

- blind condition (single or double blind) with a crossover design;
- EEG technique as experimental approach;
- investigation of the waking spontaneous EEG;
- radiofrequency range related to MP technologies

With this approach, a total of 30 studies were selected for inclusion in this review. A summary of selected studies is shown in Table 1 and Table 2. As an exception, we included the study of Lebedeva et al. (2000), as it corresponded to the first time spontaneous EEG recorded with an alternation of closed eyes and open eyes, even though it did not provide any information about the experimental design (single or double blind).

In the following chapters, we report the main results as well as the experimental protocols, materials and methods of each selected study, focusing on those parameters which will be compared and discussed in the final section (i.e. volunteers' inclusion criteria and physiological measures, SAR, RF-EMF, exposure period, etc.).

Results of literature selection

When looking at the results of the selected studies, we observed that RF-EMF signal of different MP generations was used. Indeed, about 80% of these studies investigated the effect of a 2G MP exposure on the waking spontaneous EEG, and the remaining 20% addressed the effect of higher frequencies, such as 3G and 4G of MP.

The total selected 2G studies enrolled different types of population for 900 MHz exposure. The majority of them were focused on healthy adult volunteers (23 studies), three of them on epileptic patients (Maby et al., 2006, Vecchio et al., 2012b, Curcio et al., 2015), one on adolescents (Loughran et al., 2013), one on elderly subjects (Vecchio et al., 2010) and another on comparison between adult, adolescent and elderly volunteers (Croft et al., 2010). Considering the participants' characteristics and inclusion criteria, it is noteworthy that some studies (Reiser et al., 1995, Von Klitzing, 1995, Hietanen et al., 2000, Lebedeva et al., 2000, Croft et al., 2002, D'Costa et al., 2003, Maby et al., 2006, Croft et al., 2008) did not report any information about the control criteria (i.e. exclusion of smokers, caffeine or alcohol abstention, regular sleep habits, etc.), excluding the health status. Twelve articles of the total 2G selected studies, that included healthy adults, found an increase of the alpha band power as the main result (Reiser et al., 1995, Von Klitzing, 1995, Lebedeva et al., 2000, Croft et al., 2002, Huber et al., 2002, Curcio et al., 2005, Regel et al., 2007, Croft et al., 2008, Hinrikus et al., 2008, Croft et al., 2010, Suhhova et al., 2013, Hinrikus et al., 2017); five studies found a decrease of the alpha band (D'Costa et al., 2003, Maby et al., 2006, Vecchio et al., 2012a, Perentos et al., 2013, Ghosn et al., 2015); one study found an enhanced inter-hemispheric coherence of the alpha band (Vecchio et al., 2007); the remaining five studies found no effects on the EEG spectral power (Röschke and Mann, 1997, Hietanen et al., 2000, Huber et al., 2002, Perentos et al., 2007, Regel et al., 2007). Of these studies with significant results, some of them showed a modification of EEG spectral power in other frequency bands, such as the beta band (Reiser et al., 1995, D'Costa et al., 2003, Maby et al., 2006, Hinrikus et al., 2008, Suhhova et al., 2013, Hinrikus et al., 2017), the delta band (Croft et al., 2002, Maby et al., 2006) and the theta band (Reiser et al., 1995, Maby et al., 2006). With regard to the epileptic patients in the right temporal lobe, a study has reported different brain activity reaction after a short GSM MP exposure within just 250 seconds (Maby et al., 2006). Indeed, the results showed a decrease in the spectral power of all frequency band in the healthy subjects, whereas the epileptic patients showed an increase. Similarly, a longer exposure of 45 minutes, on patients suffering from focal epilepsy with right or left hemispheric epileptogenic focus, showed an increase in the EEG power on the gamma rhythm and an enhancement of interhemispheric coherence for beta rhythm (Curcio et al., 2015). Interestingly, with the same duration of exposure reported previously (45 minutes), some authors analysed the inter-hemispheric synchronisation of the temporal and frontal EEG and compared the focal epileptic patients to the healthy subjects (Vecchio et al., 2012b). They found that the inter-hemispheric synchronisation of the patients, in the range of 8–12 Hz, was higher after exposure. On the other hand, neither 30 nor 55 minutes of exposure affected the EEG spectral power of adolescents (Loughran et al., 2013) or elderly volunteers (Croft et al., 2010). However, the inter-hemispheric synchronisation of the temporal and frontal alpha band was shown to be higher in elderly than the young adults, after 45 minutes of 900 MHz exposure (Vecchio et al., 2010).

Concerning the RF-EMF signal, 15 of total 2G selected studies focused on 900 MHz GSM signal, while others aimed to compare different 2G-like signals with each other or focused on different GSM-like signal frequency. For example, Reiser et al. (1995) exposed the participants to 902.40 MHz and also to “MEGA-WAVE 150/1” signal at 150 MHz, to have a positive control, but no information about the specific absorption rate (SAR) or power density was provided. The results showed an increased upper alpha band (9.75–12.5 Hz) and beta band after the GMS exposure and during and after the MEGA-WAVE exposure. Other authors did not find any effect, while comparing exposure to NMT 900 MHz and PCN 1800 MHz for 19 minutes (Hietanen et al., 2000). Interestingly, four studies tried to verify different effects of a continuous electromagnetic field (cw-EMF) or a pulse-modulated electromagnetic field (pm-EMF). Huber et al. (2002) and Regel et al. (2007) found enhanced alpha band power only after 30 minutes of pm-EMF exposure. Perentos et al. (2007) did not find any significant effect on EEG related to 15 minutes of exposure to cw-EMF or pm-EMF, while another study found a decrease in the spectral power of the alpha band after 20 minutes of exposure to both cw-EMF and pm-EMF, compared to sham and low-EMF (Perentos et al., 2013). Another study (Von Klitzing, 1995) found an increase in alpha band activity at 150 MHz and at a rate of 217 Hz. Three other papers, which focused on the effects on the EEG related to radiofrequency exposure at 450 MHz with different modulations, were selected (Hinrikus et al., 2008, Suhhova et al., 2013, Hinrikus et al., 2017). Results showed modification on the EEG spectral power with increased alpha and beta power. In particular, the results suggested a different sensitivity between subjects to the microwave-exposure, estimated in the rate of 13–30% of the population, which was considered as an individual variability of the cerebral physiological sensitivity (Hinrikus et al., 2008).

It is noteworthy to mention that the exposure duration (from few minutes to 55 minutes) and the SAR varied between the protocols (Table 1). Indeed, this latter parameter varied from study to study, but was maximum up to 2 W/kg. Interestingly, some authors compared different intensities of exposure with a lower and a higher SAR (from 0.003 to 1.4 W/kg) (Loughran et al., 2013, Suhhova et al., 2013). Their results suggested that the RF-EMF effects could be related to the SAR levels. Another point to emphasise is that some studies expressed the energy deposit as the power density according to the frequency, while some others did not report any RF-EMF intensity level during the exposure (Table 1). With regard to the exposure system, most studies were carried out using an MP device near the right or the left side of the head, rather than planar antennas, as listed in Table 1. It is noteworthy that few studies (Hinrikus et al., 2008, Suhhova et al., 2013, Ghosn et al., 2015, Hinrikus et al., 2017) reported a prior phantom test, to verify the interference between RF-EMF emitted by the exposure system and EEG signals, recorded by scalp electrodes during the exposure phase. Similar to the exposure duration, the EEG recording time varied from study to study, from about three minutes per condition (Röschke and Mann, 1997, Maby et al., 2006) to 30 minutes per condition (Hietanen et al., 2000, Perentos et al., 2007, Perentos et al., 2013, Yang et al., 2017). During the EEG recording, few studies included closed eyes and open eyes alternation (Lebedeva et al., 2000, Regel et al., 2007, Croft et al., 2010, Loughran et al., 2013, Ghosn et al., 2015) and the most of them opted for an open eyes condition, while some authors did not provide any information about that (Reiser et al., 1995, Maby et al., 2006). Few studies reported details about the room where the experimental sessions took place, specifying that they used a shielded room (Lebedeva et al., 2000, Croft et al., 2002, Perentos et al., 2007, Croft et al., 2010, Vecchio et al., 2012a, Perentos et al., 2013, Ghosn et al., 2015, Hinrikus et al., 2017).

Few studies (20%) on the total selection focused on 3G or 4G effects on the waking spontaneous EEG. We included in these selected publications a study on the effect of Wi-Fi on EEG brain activity (Zentai et al., 2015). Only one study (Roggeveen et al., 2015) found an increase in the alpha power, and for the beta and gamma bands, after 15 minutes of exposure to the 3G. Other studies reported different results. Yang et al. (2017) and Vecsei et al. (2018) showed a decrease in the power of the alpha band after 30 minutes of exposure to LTE signal and for 20 minutes of exposure to both UMTS and LTE signals, respectively. In particular, Yang et al. (2017) showed a decrease in the alpha and beta inter-hemispheric coherence at the frontal and temporal lobe. Three studies found no effect related to 3G or Wi-Fi signals exposure (Croft et al., 2010, Trunk et al., 2013, Zentai et al., 2015). With regard to the age of participants, all abovementioned studies were carried on adults. The only exception is Croft et al. (2010), who conducted a study on elderly and adolescent subjects. Similar to 2G studies, the exposure system and the SAR varied from study to study (Table 1). It is noteworthy that some studies (Trunk et al., 2013, Roggeveen et al., 2015, Zentai et al., 2015, Vecsei et al., 2018) realised an exposure period, during which the subject could watch a documentary to maintain their alertness. No studies on patients, such as epileptic patients, were found in the literature selection process for 3G or 4G investigations.

Discussion

The extensive use of wireless telecommunications, and especially the MP, has tremendously exposed human beings to the radiofrequency electromagnetic fields. This has raised concerns about the potential consequences on human health. Several reports have dealt with the effects of radiofrequency on cancer, fertility, sleep, endocrine functions and other physiologic functions. The scientists have used a variety of tools and methods to investigate the effects of RF-EMF, from cell culture, *in vivo* animal studies, to clinical studies. The data reported in the peer-reviewed scientific publications has been contradictory, but the most consistent results concerned the effect of radiofrequency on the waking EEG. Indeed, exposure to the radiofrequency signals was observed to modify the waking spontaneous EEG, especially in the alpha band frequency. More significantly, as shown in Figure 1, the majority of all selected studies for this review (80%) found a modification of the spontaneous EEG related to exposures to 2G system or more recent ones, as 3G and 4G, especially in the range of the alpha band. More precisely, 47% of the selected studies found a significant modification exclusively of the alpha band, while 30% found a significant modification of the alpha band and other frequency bands (delta, theta, beta and gamma). Only one study found an effect on the gamma and beta band (Curcio et al., 2015), without any effect on the alpha rhythm. Finally, 20% of the selected studies reported no significant

changes in EEG. However, the reason why the alpha band power reacts differently to RF-EMF exposure remains unclear. The main problem may lie in the use of different methods and/or different intensities and frequencies of RF-EMF, different experimental protocols and different criteria for the participant inclusion; thus, making the comparison of data more difficult.
As reported here, the most commonly investigated technology so far is the 2G, even though MP technologies have made great progress since 2G, with 3G, to 4G and now 5G. The GSM used by the 2G signal works with the pulse-modulated signal, in contrast to the 3G UMTS which functions without the periodic pulsed modulation content. The majority of 2G selected studies exposed participants to pm-EMF (see Figure 2) and reported significant effects on the brain activity. Some authors suggested that the pulsed modulation of GSM signal is necessary to induce the EEG modifications (Huber et al., 2002, Regel et al., 2007). The EEG power changes seem to be then related to the frequency modulation (Hinrikus et al., 2008). These same intrinsic properties of RF-EMF in the case of 3G and Wi-Fi continuous signals might explain the absence of significant effect on EEG of adults, after the exposure to UMTS system or 2.4 GHz Wi-Fi, suggesting here as well, that the pulsed modulation may be crucial to induce an electrophysiological reaction.

Some other interesting parameters, that vary between the studies (see Table 1 and Table 2), would be likely crucial in the absence of the final effect on the brain activity. One could argue that a short exposure time might have been the determinant of the final results (Röschke and Mann, 1997), if it is assumed that a minimum period of RF-EMF exposure is necessary to affect the EEG. On the other hand, it was shown that EEG of both healthy and epileptic patients could be affected after a very short 900 MHz exposure (Maby et al., 2006). Interestingly, concerning age of participants, all the studies which used a pm-EMF or 3G signals, found no effect on the EEG and the alpha band spectral power of the adolescents (Figure 2). Similarly, the main *in vivo* findings, obtained so far on neuronal physiology and morphology of rats and mice, suggested that young animals may not be significantly more sensitive than the adult animals (for review see Marino et al., 2011). In the same way, elderly people do not seem to be sensitive to 2G and 3G MP exposure, despite showing a higher interhemispheric coherence of the frontal and temporal alpha frequency than the young subjects (Vecchio et al., 2010). Therefore, these few studies suggest that age might be correlated to the vulnerability of the brain to the MP signal. This could be explained by a greater brain plasticity and high individual variability in adolescents (Segalowitz et al., 2010). More specifically, the alpha frequency is reported to change with age: it increases from the early stage of childhood until puberty and then starts to decline with age (Hughes, 1987, Somsen et al., 1997, Aurlien et al., 2004, Niedermeyer and da Silva, 2005). In particular, the mean posterior dominant alpha rhythm is nearly complete at the age of 16 (Marcuse et al., 2008). Moreover, some studies have showed a decrease of alpha activity in the occipital region of middle-aged subjects, compared to young adults (Başar, 2012). In contrast to the adolescents and elderly, the EEG spectral power and the spectral coherence of other types of population, such as the epileptic patients, could be affected by the RF-EMF (Figure 2), even after a short exposure to 2G signal.

It is noteworthy that there are some other remarkable differences between the research described here, comparing the methodology and the protocols. For example, the SAR—defined as the amount of absorbed non-ionising radiation power by unit of the biological tissue—is another biologically relevant factor when studying the MP-RF effect, and it differs from study to study when it is measured. As shown in Table 1 and Table 2, all studies which reported the SAR, respected the limit of 2 W/kg for the human head, as specified by the European Committee for Electrotechnical Standardisation (CENELEC, 2002). The SAR depends on several parameters, such as the MP model, the frequency band, human anatomic variability or the MP position near the head (Kainz et al., 2005, Wiart et al., 2008, Ghanmi et al., 2014). Irrespective of the frequency band, the average relative SAR is the highest in the temporal lobe on the side of the head where the MP is placed, and this cerebral region absorbs at least half of all the RF-EMF energy penetrated in the brain (Cardis et al., 2008). Obviously, this is true only when the MP is positioned near the ear, and it is not always the case, (see Table 1 and 2). Additionally, some studies have preferred a patched antenna to a commercial MP, and this increases the SAR variations within compared studies.

Furthermore, the EEG recording time varied from study to study, from few minutes to 30 minutes per condition. It is generally recommended that an EEG should last at least 20 minutes after a baseline recording period (Sinha et al., 2016). In fact, the increased length of the recording segments promotes a robust estimation of the frequency band powers (Maltez et al., 2004). Similarly, a comparison between eyes' conditions (open and closed) is an interesting means for assessment and it facilitates the chances of obtaining potentially relevant information (Sinha et al., 2016). For example, an MP effect was found only during the "eyes closed" condition, but not in the "eyes open" condition (Ghosn et al., 2015). An explanation can be found in the fact that the alpha wave's amplitude is lower when the subjects open their eyes (Barry et al., 2007, Chen et al., 2008), and so the effect of MP-RF could not be significantly detected. Conversely, when the subject is awake under the condition of physical relaxation and mental inactivity with eyes closed, the alpha rhythm is prominent, and this condition could facilitate the observation of potential effect. Some protocol approaches opted for a waking EEG recording at rest with open or closed eyes, while others used open/close eyes alternation (see Table 1 and 2). In fact, some protocols realised cognitive tasks—thanks to the video projection—or projected a documentary to maintain high alertness of the subject. However, no matter what kind of video is proposed, the alpha band is sensitive to other factors, such as noise (Shaw, 2003), and therefore, it is necessary to perform the recording in an acoustically and electrically shielded room to avoid any interference while recording the EEG (see Table 1 and 2). In addition, to highlight the possible effects on the alpha band, it could be helpful to analyse the individual alpha frequency (IAF) and to determine the frequency bands of interest for each subject, especially in the case of cognitive tasks (Vecchio et al., 2010, Vecchio et al., 2012a, Vecchio et al., 2012b). The general attributed frequency range of the alpha band is 8 to 13 Hz, but it actually varies with a normal distribution and a relatively constant deviation of 1 Hz (Klimesch, 1996), based on the genetic factors (Smit et al., 2006, Bodenmann et al., 2009) even in normal and age-matched subjects (Klimesch et al., 1990, Klimesch et al., 1993a, Klimesch et al., 1993b), memory and cognitive performance, neurological diseases (Klimesch, 1999) and brain anatomy (Nunez et al., 1978, Nunez, 1995). So, generally, when the EEG spectral power is analysed, the power distribution could be distorted with such a fixed range, and for some subjects who participate in the analyses, part of the alpha distribution could fall outside this fixed range (Haegens et al., 2014).

Another interesting physiological parameter of control, to analyse during the RF-EMF research, could be the electrocardiogram. The electrocardiogram channels should be included to detect not only spikes and sharp artefactual cardio-linked waves on the

EEG (Sinha et al., 2016)—exactly like the electrooculogram—but also because it gives useful information about the autonomic nervous system control during the recording session (Acharya et al., 2002, Joseph et al., 2004), as reported by (Ghosn et al., 2015). Indeed, the heart rate variability analysis allows the measurement of the variation in intervals between heartbeats, which could be related to a stress condition linked to the experimental environment and protocol. It is noteworthy that this physiological parameter is not affected by a MP exposure when the device is put near the head (Atlasz et al., 2006, Parazzini et al., 2007, Ahamed et al., 2008, Parazzini et al., 2013). Obviously, also a baseline recording phase could help to decrease any stress condition. Other potential interferences on EEG recording could be caused by MP-RF on the metallic electrodes of the EEG helmet. However, this potentially cofounding factor is not always taken into account. Few studies have reported this kind of interference through a prior phantom test (Suhhova et al., 2013, Ghosn et al., 2015, Yang et al., 2017).

As shown in Table 1 and Table 2, all studies reported here were carried out with a crossover blind design. Indeed, the type of experimental design is an important factor in the clinical research and a blind condition must be chosen to avoid potential problems of the subjective bias during data collection and assessment. It is also advisable to use a blind approach during the data analysis. Finally, a crossover counterbalanced randomised paradigm is recommended to minimise the biases. In this case, the real and the sham sessions should be held at the same time of the day, for each participant, to avoid any physiological modifications related to the circadian rhythm. Indeed, some physiological parameters follow a circadian rhythm in normal conditions of the light-dark cycle, such as blood pressure (Kerkhof et al., 1998) and hormone secretion (Selmaoui and Touitou, 2003), and they can interact with EEG power (Cajochen et al., 1996, Cajochen et al., 1998, Sannita et al., 1999, Tops et al., 2005, Chiu et al., 2015). Furthermore, other differences between studies concerning the subjects' participation is the schedule time, because the experimental sessions could take place on the same day and at weekly intervals (see Table 1 and Table 2). Finally, concerning the participants' characteristics and inclusion criteria, some studies did not report whether they had controlled some potentially confounding variables, such as coffee, alcohol, drugs and nicotine consumption (see Table 1 and Table 2). In fact, the consumption of these substances are well correlated to the modification of the EEG power (Reeves et al., 2002, Siepmann and Kirch, 2002, Herning et al., 2003, Teneggi et al., 2004, Deslandes et al., 2005, Domino et al., 2009, Lansbergen et al., 2011, Fisher et al., 2012, Lithari et al., 2012). Other factors that could affect EEG and alpha activity are stress hormones such as cortisol (Sannita et al., 1999, Tops et al., 2005), melatonin levels (Cajochen et al., 1996, Cajochen et al., 1998), menstrual cycle and sex hormone levels (Becker et al., 1982, Solis-Ortiz et al., 2004, Brötzner et al., 2014, Bazanova et al., 2017). For this reason, Ghosn et al. (2015) studied the young adult women, who were included in the study only during the follicular phase of their menstrual cycle, to avoid any interference with the EEG rhythm, and checked the level of the cortisol, which is considered as a biomarker of stress with the activation of the hypothalamic-pituitary-adrenal axis. In the same way, only participants with regular and matched sleep habits should be recruited, to indirectly limit the inter-variability of melatonin levels.

The differences in the methodological parameters discussed here might partially explain the inconclusive findings about the MP effect on waking spontaneous EEG. Current conclusions indicate that the MP-RF seems to affect the human EEG with the main effect on the alpha activity (Figure 1), in particular in the posterior regions of the brain. However, the nature of this modification is still unclear. When considering other neuroimaging techniques, to verify an RF-EMF effect on brain activity and physiology, the results are mixed. For example, the transcranial magnetic stimulation revealed the intracortical excitability of the motor cortex to be significantly modified during an acute exposure to GSM 900 MHz signal (Ferreri et al., 2006, Tombini et al., 2013). A functional-MRI, using a voxel-mirrored homotopic connectivity method, which quantifies the functional homotopy by providing a voxel-wise measure of connectivity between the hemispheres, revealed a modulation of the interhemispheric homotopic functional connectivity in resting state after LTE exposure (Lv et al., 2015). The functional-near infrared spectroscopy method, which allows the analysis of the oxygenation levels of the cortex through the related changes in the localised cerebral blood flow, showed a slight effect of GSM 900 MHz on the frontal cortex with a local enhancement of oxygen consumption (Curcio et al., 2009). Conversely, the functional-MRI showed no effect on the blood-oxygen-level-dependent response of a GSM 900 MHz exposure during a cognitive task (Curcio et al., 2012). Other approaches have been used to investigate changes in the regional cerebral blood flow, such as the positron emission tomography (Huber et al., 2002, Haarala et al., 2003, Huber et al., 2005, Aalto et al., 2006, Mizuno et al., 2009) and transcranial Doppler sonography, to measure the middle cerebral artery blood flow velocity (Ghosn et al., 2012). In addition to studies involving human volunteers, the effects of RF-EMF exposure on the neuronal activity have also been investigated *in vivo* and *in vitro*, trying to understand the electrophysiological bases of these modifications. These effects have been related to the interference of RF-EMF on the electrical activity and membrane ionic permeability ((Adey et al., 1982); for review see: (Adey, 1981, Cleary, 1995)). Other evidence showed an increase or a decrease in the firing rate or the burst rate (Tattersall et al., 2001, Xu et al., 2006, Partsvania et al., 2011, Moretti et al., 2013, Partsvania et al., 2013, El Khoueiry et al., 2018, Occelli et al., 2018). Therefore, further research, both *in vivo* and *in vitro*, could be helpful to shed light on RF-EMF related effects on the nervous physiology.

Conclusion

A direct and clear comparison of the main findings obtained so far is not easy, due to the considerable differences in experimental protocols and methods described here: such as the nature of RF-EMF signal and its modulation, exposure duration, exposure system position near the head, or participant inclusion criteria. However, this review allowed to emphasise that MP-RF can affect normal brain physiology and that the most consistent effect observed is in the alpha frequency. This effect is also observed after RF-EMF exposure. Some studies on adolescents (two studies included 2G system and one study included 3G system) did not indicate a higher sensitivity of this age group compared to adults. Conversely, four studies with epileptic patients showed an effect on their brain's electrophysiology related to 2G exposure. Previous systematic reviews and meta-analyses indicated that acute MP exposures did not have any cognitive or psychomotor effects (Valentini et al., 2011), with a negligible impact on attention and working memory (Barth et al., 2007).

Altogether, this review highlights that, to better investigate and understand the effects on the brain activity of any kind of MP technology, as well as the underlying physiological mechanisms and related possible health risks, further studies should be carried out with controlled protocol criteria to limit the variability of physiological state of the brain between participants. For example, it is more than recommended to use a double-blind cross-over randomised counterbalanced design, to reduce not only confounding covariates, because each participant is its own control, but also subjective bias during data collection and analysis. With this kind of protocol, experimental sessions should be performed at the same time of the day to avoid any modification in brain activity due to physiological circadian hormonal rhythms. Similarly, it is useful to study subjects under controlled physiological parameters, in order to avoid confounding factors able to induce modification of the EEG and alpha band. A starting baseline recording, an electrocardiogram, a prior phantom test and a detailed dosimetry are also helpful to limit artefacts and for more comprehensive results interpretation. Future researches should also focus on MP technologies of new generation. Indeed, as a consequence of the great evolution in MP technology and market, it is estimated that 3G/4G connections combined will be more than 50% of all global mobile connections in 2025 (GSMA, 2018) and 2G users will also migrate to the new generation networks and devices. The rigorous protocol approaches suggested here should definitely help homogenising the final results of studies, therefore leading to a better characterisation of the EEG and alpha band modifications and understanding of the effects of acute MP exposure on brain functions.

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Table 1.a 2G mobile phone exposure studies on waking spontaneous electroencephalogram with increased alpha band spectral power as main result.

Study	*Subjects*	*Design*	*Expo period and Time between sessions*	*Ctrl*	*RF-EMF*	*SAR*	*Expo system*	*Timing of expo*	*Measure-ments*	*Eyes*	*Room*	*Principal results*
Reiser et al., 1995	Healthy volunteers: 18 M, 18 F (age NR)	Single-blind, crossover	Expo conditions during the same day and every volunteer at the same time of the day	NR	MEGA-WAVE; 902.4 MHz, 217Hz; placebo	NR	MP 40 cm behind head with antenna centred	15 min	EEG, EOG	NR	NR	↑ 9.75-15.5 Hz activity, ↑ 12,75-18.5 Hz activity and ↑ 18.75-35.0 activity 15 minutes after expo
Von Klitzing et al., 1995	17 Healthy volunteers: M and F (age range 20-29 years)	Single-blind, crossover	Expo conditions during the same day and every volunteer at the same time of the day	NR	150 MHz, 217 Hz	PD < 1 μW/cm²	Coils near the neck	2 or 3 times for 15 min	EEG	C.E.	NR	↑ of the alpha activity at 10 Hz only after expo
Lebedeva et al., 2000	Healthy volunteers: 24 M (age range 20-30 years)	NR	Expo condition during the same day	NR	902.4 MHz	NR PD 0.06 mW/cm²	Antenna directed to the back of the head	15 min	EEG	C.E./O.E.	Shielded room	↑ of the global correlation dimension values during and after expo
Croft et al., 2002	Healthy volunteers: 16 M 8 F (age range 19-48 years)	Single-blind fully counterbala nced crossover	Expo condition during the same day	NR	900 MHz, 217 Hz	NR	MP placed 5 cm radial to the scalp, using a non-metallic external bracket	20 min	EEG, auditory discrimination task	O.E.	Metal shielded room	↓ 1–4 Hz activity and ↑ 8–12 Hz activity during expo
Huber et al., 2002	Healthy volunteers: 16 M (age range 20–25 years)	Double-blind balanced	Recording start at 10.20 pm	No café/no alcohol/ regular sleep habits/no medication s/no MP	pm-EMF at 900 MHz and cw-EMF	On 10g: 1 W/kg	Planar antenna on the left side of the head	30 min	Polysomno-graphy (EEG, EOG, EMG)	C.E. during sleep	Sleep laboratory	↑ 12.25-13.5 activity after pm-EMF expo
Curcio et al., 2005	Healthy volunteers: 10 M, 10 F (age range 22-31 years)	Double-blind, crossover	48 h	No MP	902.40 MHz, 217 Hz	0.5 W/kg	MP positioned 1.5 cm away from the left ear	45 min	EEG, EOG, EMG	O.E. during expo and C.E. during EEG	NR	↑ 9-10 Hz and 11 Hz activity during expo

C.E., closed eyes; Ctrl, control parameters; cw-EMF, continuous-wave electromagnetic fields; ECG, electrocardiogram; EEG, electroencephalogram; EMG, electromyogram; EOG, electro-oculogram, Expo, exposure; F, females; M, males; MP, mobile phone; NR, not reported; O.E., open eyes; PD, power density; pm-EMF, pulse-modulated electromagnetic fields; RF-EMF, radiofrequency electromagnetic fields; SAR, specific absorption rate; ↑ increased spectral power; ↓ decreased spectral power

Table 1.a Continued

Study	Subjects	Design	Expo period and Time between sessions	Ctrl	RF-EMF	SAR	Expo system	Timing of expo	Measure-ments	Eyes	Room	Principal results
Maby et al., 2006	9 healthy subjects; 6 epileptic patients (M/F and age NR)	NR	Expo condition during the same day	NR	GSM MP signal	NR	NR	250 sec	EEG	NR	NR	All frequency bands ↑ in epileptic patients during expo
Regel et al., 2007	Healthy volunteers: 24 M (age range 19-25 years)	Double-blind, counterbalanced randomised, crossover	Weekly interval Between 2:45- 6 pm	No smokers/no café/no alcohol/ regular sleep habits/no medications/ no MP	pm-EMF at 900MHz and cw-EMF	On 10g: peak of 1 W/kg	Head placed between two planar patch antennas with exposition on the left hemisphere	30 min	Cognitive Tasks, EEG, EMG, EOG, ECG	C.E/O.E.	NR	↑ 10.5-11 Hz activity 30 minutes only after pm-EMF expo
Vecchio et al., 2007	Healthy volunteers: 10 M (age range 20-36 years)	Double-blind, crossover	Weekly interval	No café/no alcohol/ regular sleep habits/no medications/ no MP	902.40 MHz, 217 Hz	NR	MP placed at 1.5 cm from the left ear by a helmet	45 min	EEG, EOG	C.E.	NR	↑ interhemispheric coupling of alpha rhythms between the temporal areas and ↓ between the frontal areas during expo
Croft et al., 2008	Healthy volunteers: 46 M, 74 F (age range 18-69 years)	Double-blind, counterbalanced crossover	Weekly interval	NR	895 MHz, 217 Hz	On 10g: without electrodes peak of 0.110 W/kg	MP over right or left temporal region	30 min	EEG, EOG	O.E.	NR	↑ 8–12 Hz activity during expo
Hinrikus et al., 2008	4 groups of healthy volunteers: 10 M 9 F; 4 M 9 F; 8 M 7 F; 8 M 11 F (age range 19-30 years)	Double-blind, counterbalanced crossover	Expo condition during the same between 9 am and noon	No medications/ regular sleep habits/ prior phantom test	450 MHz at different modulation	On 1g: 0.303 W/kg	Antenna 10 cm from left ear	10 min	EEG	C.E.	Dark room	↑ EEG especially in alpha and beta bands
Croft et al., 2010	Healthy 42 young adults, of which 21 F (age range 19-40 years)	Double-blind, counterbalance, crossover	At least 4-day interval	No café/no alcohol/no smokers/no medications/ no substance abuse	894.6MH, 217 Hz	On 10g: 0.7 W/kg for the 2G	2G MP placed on one side of the head and a 3G model handset on the other side (temporal region)	55 min	EEG, EOG, cognitive tasks	C.E/O.E., only O.E. analyses	Sound-attenuated metal shielded room	↑ 8-12 activity only in young adults during 2G expo

Table 1.a Continued

Study	*Subjects*	*Design*	*Expo period and Time between sessions*	*Ctrl*	*RF-EMF*	*SAR*	*Expo system*	*Timing of expo*	*Measure-ments*	*Eyes*	*Room*	*Principal results*
Vecchio et al., 2010	Healthy volunteers: 16 elderly volunteers, of which 11 F (age range 47-84 years); 15 young M (age range 20-37 years)	Double-blind, crossover	Weekly interval	No café/no alcohol/ regular sleep habits/no MP/post-menopausal	902.40 MHz, 217 Hz	Maximal measure 0.5 W/kg	MP placed at 1.5 cm from the left ear by a helmet	45 min	EEG, EOG	C.E. during EEG/O.E. and walking during Expo	NR	↑ inter-hemispheric coherence of frontal and temporal 8–12 Hz activity during expo in elderly compared to young subjects
Suhhova et al., 2013	Heathy volunteers: 9 M and 6 F (age range 23-32 years)	Single-blind, randomised, randomised counter-balanced crossover	Expo condition during the same day with 15 min interval	No medications/ regular sleep habits/ prior phantom test	450 MHz, at 40 Hz modulation	On 1g: 0.003 W/kg and 0.303 W/kg	Antenna 10 cm from left ear	10 min	EEG	C.E.	Dark room	↑ beta 2, beta 1 and alpha frequency at the higher SAR level; ↑ beta 2 band at lower SAR level
Curcio et al., 2015	12 epileptic patients, of which 5 F age range 21-79 years)	Double-blind, crossover, randomised, counterbalanced	Weekly interval	No café/no alcohol/ regular sleep habits/no MP	902.40 MHz, 217 Hz	Maximal measure 0.5 W/kg	MP placed at 1.5 cm from the side of the head with epileptic focus	45 min	EEG, EOG	C.E.	NR	↑ gamma in partieto-occipital and temporal areas
Hinrikus et al., 2016	Healthy volunteers: 8 M and 7 F (age range 21-24 years)	Single-blind, randomised, randomised counter-balanced crossover	Expo condition during the same between 9 am and noon	No medications/ regular sleep habits/ prior phantom test	450 MHz, at 7, 40, 1000 Hz modulati on	On 1g: 0.303 W/kg	Antenna 10 cm from left ear	15 min	EEG	C.E.	Acoustically and electrically shielded room	↑ alpha and beta band only after 40 Hz modulated exposure

Table 1.b 2G mobile phone exposure studies on waking spontaneous electroencephalogram with decreased alpha band spectral power as main result.

Study	Subjects	Design	Expo period and Time between sessions	Ctrl	RF-EMF	SAR	Expo system	Timing of expo	Measure-ments	Eyes	Room	Principal results
D'Costa et al., 2003	Healthy volunteers: 5 M, 5 F (age range 18-30 years)	Single-blind randomised	Expo condition during the same day	NR	900 MHz, 217 Hz	NR	MP's antenna positioned 2 cm away from the occipital region	25 min	EEG	C.E.	Silent room	↓ 8–13 Hz and 13–32 Hz activity during expo
Maby et al., 2006	9 healthy subjects; 6 epileptic patients (M/F and age NR)	NR	Expo condition during the same day	NR	GSM MP signal	NR	NR	250 sec	EEG	NR	NR	All frequency bands ↓ in healthy volunteers
Vecchio et al., 2012	Healthy volunteers: 8 M, 3F (age range 24-63 years)	Double-blind, crossover, placebo-controlled	Weekly interval	No café/no alcohol/ regular sleep habits/no MP/post-menopausal	902.40 MHz, 217 Hz	Maximal measure 0.5 W/kg	MP placed at 1.5 cm from the left ear by a helmet	45 min	EEG, EOG, go/no-go task	O.E. during EEG/O.E. and walking during Expo	Shielded room	↓ 10-12 Hz event-related desynchronization and faster reaction time to go stimuli after expo
Perentos et al., 2013	Healthy volunteers: 37 M, 35 F (mean age 24,5 years ± 5,4)	Double blind, crossover	Expo condition during the same day.	No café/no alcohol/no MP	cw-EMF, pm-EMF at 900MHz, ELF	On 10g: cw-EMF 1,95 W/kg, pm-EMF 0,06 W/kg	Model handset placed according to the standard ear-to-mouth position, over the right hemisphere	20 min	EEG, EOG,	O.E.	Metal shielded room and shielded EEG amplifiers	↓ 8-12 activity during pm-EMF and cw-EMF. No effect of ELF expo

Ghosn et al., 2015	Healthy volunteers: 13 M, 13 F (mean age 23,5 years ± 3,1)	Double blind, randomised, counter-balanced, crossover	Weekly interval and each session at the same time of day	No café/no alcohol/no medications/ no smokers/ regular sleep habits/no MP/menstrual follicular period/ prior phantom test	900 MHz, 217 Hz	On 10g: peak at 0,93 W/kg	MP positioned against the left ear	26 min	EEG, ECG, EDR, Biomarkers of stress	C.E./O.E.	Electrically shielded room	↓ 8-12 Hz activity only during closed-eyes condition during and after expo

Table 1.c No effect of 2G mobile phone exposure studies on waking spontaneous electroencephalogram.

Study	***Subjects***	***Design***	***Expo period and Time between sessions***	***Ctrl***	***RF-EMF***	***SAR***	***Expo system***	***Timing of expo***	***Measure-ments***	***Eyes***	***Room***	***Principal results***
Roschke and Mann, 1997	Healthy volunteers: 34 M (age range 21-35 years)	Single-blind, placebo-controlled, crossover	Expo condition during the same day between 9 – 12 am	No café/no alcohol/no smokers/no medications	900 MHz, 217 Hz	NR PD 0.05 W/cm²	Aerial 40 cm from the vertex	3,5 min	EEG	C.E.	NR	None
Hietanen et al., 2000	Healthy volunteers: 10 M, 9 F (age range 32-57 years)	Single-blind, randomised	Expo condition during the same day	NR	NMT 900 MHz (G1); GSM 900 MHz; PCN 1800 MHz	On 10g: 0.851 mW/kg with electrodes; 0.818 mW/kg without electrodes	MP 1 cm away from the head	19 min	EEG	C.E.	Shielded EEG amplifiers	None
Huber et al., 2002	Healthy volunteers: 16 M (age range 20–25 years)	Double-blind balanced	Recording start at 10.20 pm	No café/no alcohol/ regular sleep habits/no medications/ no MP	pm-EMF at 900 MHz and cw-EMF	On 10g: 1 W/kg	Planar antenna on the left side of the head	30 min	Polysomnography (EEG, EOG, EMG)	C.E. during sleep	Sleep laboratory	No effect after cw-EMF exposure

Perentos et al., 2007	Healthy volunteers: 6 M, 6 F (age range 19-32 years)	Double-blind, fully counterbalanced crossover	Expo condition during the same day	NR	pm-EMF at 900 MHz and cw-EMF	On 10g: peak of 1.56 W/kg	Model handset on left ear region	15 min	EEG	C.E.	Shielded room	None
Regel et al., 2007	Healthy volunteers: 24 M (age range 19-25 years)	Double-blind, counterbalanced randomised, crossover	Weekly interval Between 2: 45- 6 pm	No smokers/no café/no alcohol/ regular sleep habits/no medications/ no MP	pm-EMF at 900MHz and cw-EMF	On 10g: peak of 1 W/kg	Head placed between two planar patch antennas with exposition on the left hemisphere	30 min	Cognitive Tasks, EEG, EMG, EOG, ECG	C.E/O.E.	NR	No effect after cw-EMF expo

Table 1.c Continued

Study	***Subjects***	***Design***	***Expo period and Time between sessions***	***Ctrl***	***RF-EMF***	***SAR***	***Expo system***	***Timing of expo***	***Measure-ments***	***Eyes***	***Room***	***Principal results***
Croft et al., 2010	Healthy volunteers: 41 adolescents, of which 20 F (age range 13-15 years); 20 elderlies, of which 10 F (age range 55-70 years)	Double-blind, counterbalanced, crossover	At least 4-day interval	No café/no alcohol/no smokers/no medications/ no substance abuse	2G: 894.6MH, 217 Hz	On 10g: 0.7 W/kg for the 2G	2G MP placed on one side of the head and a 3G model handset on the other side (temporal region)	55 min	EEG, EOG, cognitive tasks	C.E/O.E., only O.E. analyses	Sound-attenuated metal shielded room	No effect of 2G expo on adolescents and elderly
Loughran et al., 2013	Healthy volunteers: 12 adolescents M, 10 adolescents F (age range 11–13 years)	Double blind, randomised, counter-balanced, crossover	Weekly interval and each session at the same time of day	No café/ regular sleep habits/no MP	900 MHz	Low SAR: 0,35 W/kg High SAR: 1,4 W/kg	Head placed between two planar antennas with exposition on the left hemisphere	30 min	EEG, EOG, ECG, Cognitive tasks	C.E/O.E.	NR	No reliable effect on EEG

Table 2 3G, 4G and Wi-Fi RF-EMF exposure studies on waking spontaneous electroencephalogram and main results (increased alpha band spectral power, decreased alpha band spectral power, no effect)

Study	*Subjects*	*Design*	*Expo period and Time between sessions*	*Ctrl*	*RF-EMF*	*SAR*	*Expo system*	*Timing of expo*	*Measure-ments*	*Eyes*	*Room*	*Principal results*
Roggeveen et al., 2015	Healthy volunteers: 31 F (mean age 26,7 years ± 8,5)	Single-blind, crossover	1-day interval. Between 9 am – 5 pm	No café/no alcohol/no smokers	3G: 1.9291 to 1.9397 GHz	0,69 W/kg as reported in the manual	MP positioned against the left ear	15 min	EEG, EOG	O.E. watching a movie	Electrically non-shielded room	↑ alpha, slow-beta, fast-beta, and gamma bands during expo
Yang et al., 2016	Healthy volunteers: 25 M (mean age 30,2 years ± 2,7)	Double-blind, counter-balanced	Weekly interval	No café/no alcohol/no smokers/ prior phantom test	LTE 2.573 GHz	On 10g: 1.34 W/kg with electrodes and 1.27 without electrodes	Standard dipole placed 1 cm away from the right ear	30 min	EEG	C.E.	Anechoic room	↓ spectral power and the interhemispheric coherence in alpha and beta bands spectral power of frontal and temporal regions
Vecsei et al. 2018	Healthy volunteers. UMTS study: 34 of which 20 W (aged 20 years ± 3) and LTE study: 26 of which13 W (mean age 21 years ± 3)	Double blind, randomised, counter-balanced, crossover	At least one week interval. Each session at the same time of day between 8 am - 6 pm	No café/no alcohol/no smoking/no medications	3G UMTS 1947 MHz/ 4G LTE 1750 MHz	On 1g: 3G 1.75 W/kg / 4G 1.80 W/kg	Patch antenna placed 7 mm away from the right ear	20 min	EEG, EOG, Stroop test	O.E. watching a muted film	Dimly lit room	↓ alpha band during and after both 3G and4G exposure over the whole scalp
Croft et al., 2010	Healthy volunteers: 41 adolescents, of which 20 F (age range 13-15 years); 42 young adults, of which 21 F (age range 19-40 years); 20 elderlies, of which 10 F (age range 55-70 years)	Double-blind, counterbalanced crossover	At least 4-day interval	No café/no alcohol/no smokers/no medications/ no substance abuse	3G: 1900MHz, 125mW	On 10g: 1.7 W/kg for the 3G	2G MP placed on one side of the head and a 3G model handset on the other side (temporal region)	55 min	EEG, EOG, cognitive tasks	C.E/O.E., only O.E. analyses	Sound-attenuated metal shielded room	No effect of 3G expo

C.E., closed eyes; Ctrl, control parameters; EEG, electroencephalogram; EOG, electro-oculogram, Expo, exposure; F, females; M, males; MP, mobile phone; NR, not reported; O.E., open eyes; RF-EMF, radiofrequency electromagnetic fields; SAR, specific absorption rate; ↑ increased spectral power; ↓ decreased spectral power

Table 2 Continued

Study	Subjects	Design	Expo period and Time between sessions	Ctrl	RF-EMF	SAR	Expo system	Timing of expo	Measurements	Eyes	Room	Principal results
Trunk et al., 2013	Healthy volunteers: 17 young volunteers, of which 9 F (mean age 21,7 years ± 3,47); 26 young volunteers, of which 12 F (mean age 24,08 years ± 6,68)	Double-blind	Weekly interval	NR	3G UMTS 1947 MHz	On 1g:1.75 W/kg	Patch antenna placed next to the right ear	30 min	Event-related potentials, spontaneous EEG, EOG, Audiometry	O.E. watching a movie during EEG	NR	None
Zentai et al., 2015	Healthy volunteers: 15 F (mean age 23,3 years ± 0.6)	Double-blind, randomised, counter-balanced, placebo-controlled	Minimum 1-week interval and each session at the same time of the day	No café/no alcohol/ regular sleep habits	2.4 GHz Wi-Fi	On 10g: 99.22 mW/ kg	Exposure unit 40 cm away from the head	60 min	EEG, EOG, psychomotor vigilance test	O.E. watching a movie	Anechoic chamber	None

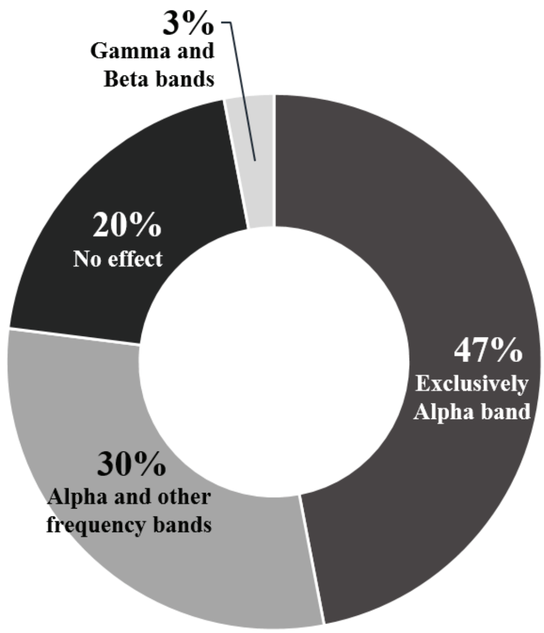

Figure 1

Overview of 30 total selected studies which investigated the effect of the radiofrequency electromagnetic fields on human waking spontaneous EEG. Total of studies includes power spectral density and interhemispheric coherence analysis. The 47% of studies found a significant modification exclusively of the alpha band, the 30% found a significant modification of the alpha band and other frequency bands (delta, theta, beta and gamma), the 3% (only one study) found an effect on the gamma and beta band, without any effect on the alpha rhythm, the 20 % reported no significant effect on the EEG.

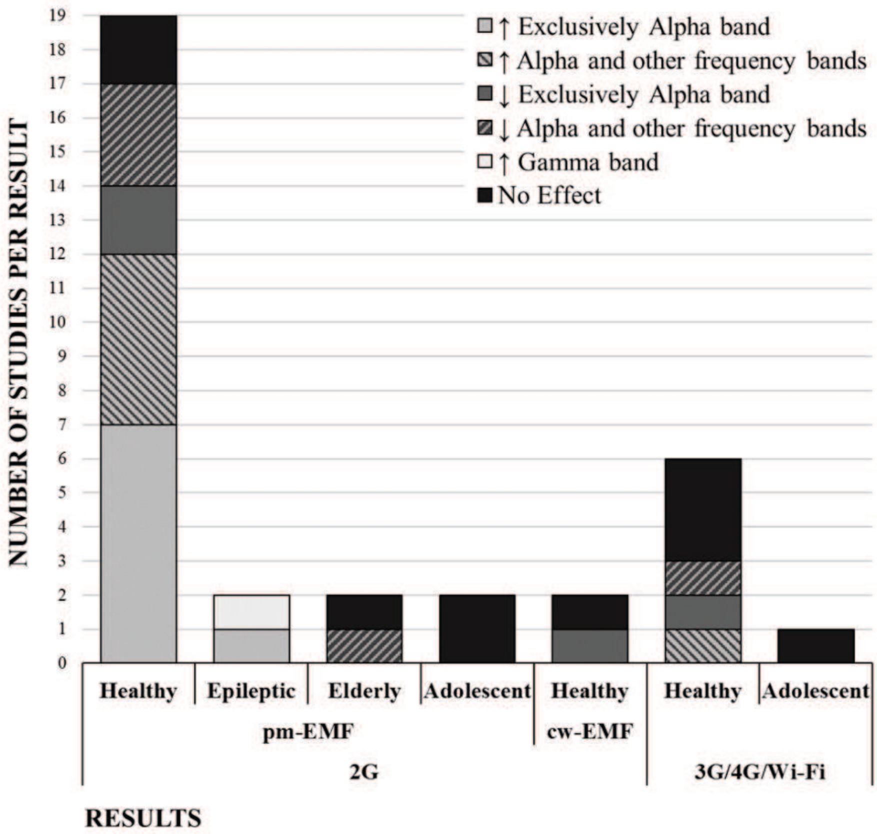

Figure 2

Overview of selected studies which investigated the effect of 2G system (450 MHz studies are also included) or more recent systems like 3G, 4G and Wi-Fi signals, on the power spectral density of waking spontaneous EEG. Studies which realised a comparison between two or more different kinds of RF-EMF or types of population, and obtained two different results, are considered twice.

↑ increased spectral power; ↓ decreased spectral power