

UNIVERSITY OF PÉCS

DOCTORAL SCHOOL OF BIOLOGY AND SPORTBIOLOGY

**The possible effects of Wi-Fi electromagnetic field exposure on
human cognitive functions**

PhD thesis

Norbert Zentai



Supervisor:

Dr. István Hernádi
associate professor

PÉCS, 2019

1. Introduction

The functioning of the healthy human body is normally not affected adversely by the natural background electromagnetic (EM) radiation. However, in the past few decades, the human body has been increasingly exposed to artificial non-ionizing microwave and radiofrequency (RF) electromagnetic fields (EMFs) of varying frequency and intensity, among others personal wireless EMF (mobile phones, DECT and Wi-Fi) sources have become exponentially popularized. In line with the rapid global deployment of wireless RF-EMF technologies, there are a growing number of scientific studies and expert reviews dedicated to the potential adverse effects of RF-EMF on biological systems (IARC, 2011, WHO, 2011, EFHRAN, 2012). Though all mobile communication device operates at EM energy levels that cannot disrupt chemical bonds, the non-ionizing radiation emitted by them may interfere with neurocognitive processes in the human brain. Although a series of studies have focused on the question of how electroencephalographic activity (EEG) is affected by RF-EMF exposure emitted by mobile phones in the 450–2700 MHz frequency range with 0.1–2 W output power, the findings are still inconsistent (Juutilainen et al. 2011). Some studies found evidence that specific alterations in EEG recordings may be associated with exposure to RF-EMF (Borbely et al. 1999; Croft et al. 2010; Curcio et al. 2005; Huber et al. 2002; Leung et al. 2011; Reiser et al. 1995). In contrast, other studies found no effect of RF-EMF on any observed EEG patterns (Hietanen et al. 2000; Kleinlogel et al. 2008; Röschke and Mann, 1997; Trunk et al. 2013). Similarly, the results in studies investigating the effect of RF-EMF on cognitive functions are also controversial (van Rongen et al. 2009; Kwon and Hamalainen, 2011). Several studies proved modulatory effect of EMF on the performance in cognitive tasks (Preece et al. 1999; Koivisto et al. 2000a; 2000b; Edelstyn and Oldershaw, 2002), others found no effect (Preece et al. 2005; Regel et al. 2007; Stefanics et al. 2008; Trunk et al. 2013, 2014, 2015; Haarala et al. 2003, 2004, 2005, 2007).

Most of the EMFs emitted by Wi-Fi-compatible devices can be similarly described as EMFs emitted by mobile phones. Exposure to RF emitted by WLAN systems has been raising¹ a serious public concern about possible human health effects. According to the rapid spreading of the use of Wi-Fi compatible devices several papers studied the absorption and potential health effects of Wi-Fi RF-RMF in animals. Concerning the physiological effects numerous studies emphasize the oxidative damage and alternations on metabolic parameters

¹ <https://www.abiresearch.com/press/abi-research-anticipates-more-20-billion-cumulativ/>

in blood caused by 2.4 GHz wireless device EM radiation (Gumral et al. 2009; Shekoohi-Shooli et al. 2016). Studies relating to neurophysiological effects vary in methodology and have contradictory results. Nevertheless, most of the results reveal various modifying effects to the nervous system in animals. Exposure to 2.4 GHz Wi-Fi EMF induced various oxidative stress responses in cortical areas of the brain (Celik et al. 2016), such as significant decrease in PKC activity in the hippocampus and increased glial cell numbers in the exposed brain tissue (Paulraj and Behari, 2006); decreased A, C and E-vitamin concentration in the cortex (Naziroglu and Gumral, 2009); and impaired unimodal and crossmodal integration of information in the brain (Hassanshahi et al. 2017). Interestingly, in transgenic mice with Alzheimer's disease-like cognitive impairment long-term Wi-Fi exposure has been suggested to improve memory functions (Banaceur et al. 2013). In sum, unified conclusion from these results cannot be deduced, however, they draw the attention to the potential diverse health effects of Wi-Fi EMF radiation.

To assess the radiation features of WLAN EMF on human body up to now mainly computational absorption calculations have been performed. Studies in this field estimate the amount and peak values of absorbed radiation, the patterns of radiation and dependence of absorption on power density, on gender and age (Schmid et al. 2007a; Martinez-Burdalo et al. 2009; Wang and Fujiwara, 2005; Wiart et al. 2008; Findlay and Dimbylow, 2010; Fiocchi et al. 2014). The results indicate that the absorbed radiation in several settings, even with the maximum permitted output power were well below the safety limits of the current international guidelines. However, it is notably highlighted that the absorption rate largely varies by the age and phenotypic individual characteristics of the exposed subjects.

However, up till now only a few studies have investigated the best laboratory practice to be applied in implementing an exposure system specifically designed for Wi-Fi experiments to examine the potential effects of WLAN-EMF on human cognitive functions. Papageorgiou et al. (2011) conducted a non-computational study with healthy human participants to determine whether Wi-Fi irradiation from a distance of 1.5 m affects the performance in a linguistic task and adjacent brain oscillatory activity measured by event related potentials (ERP). In that same setting Maganioti et al. (2010) investigated the potential changes in EEG spectral components performing a Wechsler working memory test. Interestingly, Papageorgiou et al. found a gender difference: the amplitude of the P300 ERP component decreased for males and increased for females during cognitive task performance in genuine Wi-Fi exposure; whereas Maganioti et al. revealed a significant decrease of

performance for females in alpha and beta spectral components associated with exposure to Wi-Fi-EMF. Nevertheless, the precise dosimetry, accurate procedures and results (f values, power) have not been published, thus their results can not be interpreted as representative evidences of the effects of Wi-Fi EMF irradiation on cognitive performance measures.

2. Aim

Consequently, examination of potential modulatory effects of Wi-Fi EMFs on human cognitive performance has become a high-priority field of research. Therefore, the present study aims to evaluate the complex RF exposure characteristics of WLAN technology and describe the design and evaluation of a specific WLAN exposure system using Wi-Fi modulation made suitable for human studies aiming at investigating potential biological effects of Wi-Fi exposure, particularly on human brain function.

Our aims were to:

- Design a custom-built, stable, well-controlled Wi-Fi exposure system suitable for human studies.
- Evaluate the exposure system with precise dosimetry on a) the quality and output power of the exposed signal, b) the stability of the exposure system.
- Investigate the potential effects of a single Wi-Fi exposure (60 min long, IEEE 802.11 b/g, 2.4 GHz, 100 mW output power, from a distance of 40 cm) on the spontaneous (resting state) EEG activity.
- Investigate – in the same experimental arrangement – the potential effects of the exposure on human cognitive performance in the psychomotor vigilance (PVT) test.

3. Materials and Methods

3.1. The Wi-Fi exposure system and dosimetry

In the present study, a WLAN exposure system was constructed from commercially available parts that were all produced by MikroTik² (Riga, Latvia). During the initial testing of the new WLAN exposure system for the purpose of biological experiments, two types of mPCI (mini Peripheral Component Interconnect) router board cards, one 802.11 a/b/g (type R52) and one 802.11 a/b/g/n capable (type R52n) were evaluated nominally with 20–80 mW

² <https://mikrotik.com/>

(13–19 dBm) and 20–200 mW (13–23 dBm) peak power, respectively. Both the R52 and R52n router board cards were operated only on b/g transfer mode. The WLAN system consisted of an access point (AP) and a client unit (CU). The AP consisted of a commercially available router motherboard MikroTik RB433AH, the CU consisted of a router motherboard MikroTik RB411AH. The system ran on RouterOs Level5 v4.10 with AP support. The motherboards were placed in custom-built indoor aluminum cases (RB433U, RB411) with AC/SWI 2 dBi Swivel omnidirectional antennas and operated with Power Over Ethernet (POE) power supply. The AP and the CU were both controlled by a personal computer (PC) applying WinBox v2.2.18 software (MikroTik Co, Riga, Latvia) running under MS Windows operating system (Microsoft Co, Redmond, US).

The free-field measurements were performed in the National Institute of Environmental Health (NIEH) "Frédéric Joliot-Curie" National Research Institute for Radiobiology and Radiohygiene (NRIRR) laboratory in Budapest³. Both the AP and CU were placed in an anechoic chamber and the RF field near the client was measured with a Narda⁴ PMM 8053 field meter (Narda Safety Test Solutions, Savona, Italy) with a wide-band E-field probe. The distance between the CU antennas and the field meter probe was 40 cm, which is aimed at modelling the typical distance between the user and the personal computer (e.g., notebook) in which Wi-Fi antennas are often mounted in the frame of the screen. Two PCs were used for data acquisition were placed outside the anechoic chamber. The effects of various settings were then investigated: the electric field was measured with different protocols (TCP, UDP), channels (1–13, 2412–2472 MHz), modes (802.11b/g), and data rates. We generated the wireless connection between the AP and the CU and the continuous data transmission via bandwidth test.

The absorption in the human body of the RF energy emitted by the Wi-Fi exposure system was foremost performed by computational modeling of SAR. The commercial simulation platform SEMCAD X⁵ was used to estimate the SAR levels in realistic anatomical human models. The results were presented in terms of 10 g averaged SAR over tissues. Originally, we used for the calculations 1W output power, 2.4 GHz and a duty cycle of 100% of the Wi-Fi signal, however data were needed to be normalized by considering a nominal input power of 100 mW and a duty cycle of 66.19%. Two whole body, realistic

³ <http://www.osski.hu/>

⁴ http://narda-sts.it/narda/story_en.asp

⁵ <https://www.speag.com/products/semcad/EuCAPAnimation/>

human models were used, both from the Virtual Family (“Ella” female, “Duke” male) made available for research (Christ et al. 2010). The two models were formed through the “Poser” tool (IT’ IS Foundation⁶) available within the SEMCAD X package software to obtain various sitting postures.

3.2. Possible effect of acute Wi-Fi exposure on spontaneous EEG

Participants and procedures of the spontaneous EEG measurements. The sample comprised data from 25, healthy, right-handed, university student participants (15 females, mean age 23.3 years, SEM: 0.6) in the sEEG study. The participant’s head was exposed to either genuine Wi-Fi or sham irradiation in two separate sessions lasting 60 min each, with a minimum 1-week interval between sessions, were designed in a double-blind, crossover fashion. During the whole session, the participant’s task was to watch a documentary clip in a relaxed fashion with the sound turned off. Electroencephalographic brain potentials were recorded from three Ag/AgCl electrodes at midline Fz, Cz, and Pz sites according to the international 10–20 system. The nose served as reference and the forehead as ground. For artifact rejection purposes, horizontal and vertical eye movements were monitored by two electrooculogram (EOG) electrodes placed above the left and below the right outer canthi, respectively. The impedance at the start of each session was under 5 kOhm at all electrodes. First, we amplified the detected signal, then applied different filters (from 0.5 to 100–200 Hz) to exclude the distortion components. Finally, we converted the analogue signal to digital information with an A/D converter (CED⁷ Power 1401, Cambridge, UK). The EEG was recorded continuously at a sampling rate of 1 kHz with an analog band-pass filter of 0.16–150 Hz and a 50 Hz notch filter. Data were stored on a PC for off-line analysis. Each session (either genuine Wi-Fi or sham exposure) was comprised of three, 10 min recording blocks (directly before/Pre, in the middle/Mid and right after/Post exposure).

Analysis of spontaneous EEG data. EEG data, recorded by CED Spike2 were analyzed off-line on a PC using built-in and self-developed functions, as well as the freeware EEGLAB toolbox⁸, in Matlab programming environment (MathWorks, Natick, MA). Data were analyzed at three recording sites (Fz, Cz and Pz). Continuous data were filtered between 0.5 and 40 Hz, and then segmented into 2 s epochs. Trials exceeding ± 100 microV were rejected from further analyses. The fast Fourier transform (FFT) algorithm was applied to

⁶ <https://www.itis.ethz.ch/>

⁷ <http://ced.co.uk/>

⁸ <http://sccn.ucsd.edu/eeglab/>

epoched data. Log-transformed power values were calculated for pre-defined frequency bands – identical to previous studies – for each block for statistical analyses (delta: 1–3 Hz, theta: 4–8 Hz, alpha1: 9–10 Hz, alpha2: 11–12 Hz, beta1: 13–18 Hz, and beta2: 19–32 Hz). Three separate analyses were performed to examine the difference between genuine Wi-Fi and sham exposure conditions. First, EEG spectral power was analyzed as follows: three-way rANOVA of sessions (Genuine, Sham), blocks (Pre, Mid, Post) and electrodes (Fz, Cz, Pz) were separately performed for the six frequency bands. In the second analysis, the 10 min Post exposure block was divided into 2 min time segments. The hypothesized transient after-effects of Wi-Fi exposure were analyzed by rANOVAs of sessions (Genuine, Sham), segments (Seg1–5) and electrodes (Fz, Cz, Pz) in the Post block. In the third analysis, gender specific effects of Wi-Fi exposure were tested on all frequency bands and all segments by repeating the previous analysis and including gender (Male, Female) as a between-subject factor.

3.3. Possible effect of acute Wi-Fi exposure on cognitive performance in the psychomotor vigilance test

Participants and procedures of the psychomotor vigilance test. PVT data were measured and analyzed in a final sample of 19 healthy, right-handed, university student participants (10 females, mean age 21.0 years, SEM 0.4). In a similar setting as sEEG measurements, the participant's head was exposed to either genuine Wi-Fi or sham irradiation in two separate sessions lasting 60 min each, with a minimum 1-week interval between sessions, in a double-blind, crossover design. The PVT test was implemented by the open-source Psychology Experiment Building Language (PEBL, Mueller and Piper, 2014) framework installed on a standard PC. In the two experimental sessions (genuine Wi-Fi or sham), the participants performed the PVT task in 4 blocks of trials lasting 15 min each. In each trial, the task required the participant to react as soon as possible to a red dot presented on the center of the screen. Participants responded by pressing the space bar on a keyboard and the stimuli were presented with a stimulus-onset asynchrony (SOA). In each 15 min block 106 RT were registered per person. The trials <100 ms or >2000 ms were rejected from the final analysis. In the first three blocks (Blocks I–III), the participants were exposed to 60 min of genuine Wi-Fi or sham, the blocks were separated by 5 min intervals. The total duration of Wi-Fi exposure lasted from the beginning of Block I till the end of Block III + 5 min break. After Block III and a following 5+20 min break, a last post exposure block (Block IV) was recorded.

During the PVT task, participants were asked to fill visual analog scales (VAS, Aitken, 1969) to inform the pre- and after-task subjective fatigue, attention and motivation ratings before and after Block I–III.

Analysis of psychomotor vigilance test and visual analog scales data. The RT data were automatically saved to a file for later analysis. Six performance measures were subjected to repeated measures ANOVAs according to previous PVT studies: Mean reaction time (RT), Mean number of lapses (lapses of attention defined as reaction times greater than 500 ms), inverse RT ($1/\text{mean RT} \times 1000$; henceforth $1/\text{RT}$), the variability of responses (defined as the coefficient of variation, SD/mean for RTs), the fastest reaction times (10th percentile), and the slowest reaction times (90th percentile). To obtain a better insight into the potential temporal changes in performance, PVT data were divided into 3 equal intervals (approx. 5 min each) in each experimental block. First, PVT data from the three exposure blocks were tested with rANOVA with the combination of factors as the sessions (Genuine, Sham), blocks (Block I–III), and intervals (Int 1–3). In the second analysis, gender specific effects of Wi-Fi exposure were tested by repeating the previous analysis including gender (Male, Female) as a between-subject factor. In the third analysis, we addressed the question of whether performance would be different between the exposure and post-exposure blocks in the two exposure conditions (Genuine, Sham). To analyze this, rANOVA was performed for two of the recording blocks only: Block III and Block IV with the factors of sessions and intervals. The fourth analysis addressed changes in the subjective fatigue, attentional and motivational state over the course of the experiment. These values were analyzed by rANOVA with the factors of sessions (Genuine, Sham) and blocks (Block I–III).

4. Results

4.1. Dosimetry outcomes and final settings of the Wi-Fi exposure system

The currently investigated WLAN exposure system, according to the detailed dosimetry, we conclude that the exposure is more reliable and stable when both antennas are active and positioned vertically. The best signal quality and strength on IEEE 802.11 b/g were observed using channel 9 (2452 MHz), 20 dBm/100 mW output power, UDP mode, R52n mPCI card.

In the computational modeling of SAR we evolved a setting which better mimics a realistic e.g. a notebook use scenario. To estimate the SAR levels of Wi-Fi emitted RF-EMF

realistic anatomical human models were used. As expected, the target tissues closer to the Wi-Fi source (forehead skin, grey matter, and white matter) were showing higher SAR values.

4.2. Effects of Wi-Fi exposure on spontaneous EEG

To test for possible effects of Wi-Fi exposure on sEEG measures, we analyzed mean amplitudes of power spectra separately in the delta, theta, alpha1, alpha2, beta1 and beta2 EEG frequency bands. In the first analysis, rANOVA demonstrated no significant effects of genuine Wi-Fi exposure on sEEG spectral amplitudes. Significant main effect of time spent in the task was detected on the alpha1 amplitude [Block: $F(2,48)=4.74$, $p<0.05$, partial eta-squared=0.16]. Mean differences were caused by the amplitude increase in the third block (mean: 1.33 μV , SEM: 0.09) when compared to the first (mean: 1.27 μV , SEM: 0.08) or second (mean: 1.26 μV , SEM 0.08) blocks.

In the second analysis, to reveal the potential after-effect of exposure, the post-exposure (Post) block was divided into 2 min long segments and we found a significant segment main effect [$F(4,96)=4.77$, $p<0.001$, partial eta-squared=0.16] in the alpha1 band. Tukey HSD post hoc test revealed that the fourth segment (Seg 4, mean: 1.25 μV , SEM: 0.07) differed from the first (Seg 1, mean: 1.37 μV , SEM: 0.1), second (Seg 2, mean: 1.36 μV , SEM: 0.09) and third (Seg 3, mean: 1.35 μV , SEM: 0.1) segments. A significant segment main effect was also found in the alpha2 band ($F(4,96)=2.59$, $p<0.05$, partial eta-squared=0.09). Tukey HSD post hoc tests showed that the alpha2 amplitude in the fourth segment (Seg 4, mean: 0.92, SEM: 0.05) was significantly lower compared to the first segment (Seg 1, mean: 0.97, SEM: 0.06). Furthermore, we found a significant segment main effect in the beta2 band ($F(4,96)=10.75$, $p<0.01$, partial eta-squared=0.3). Post hoc tests showed that the amplitude in the fourth (Seg 4, mean: 0.46 μV , SEM: 0.02) and fifth (Seg 5, mean: 0.47, SEM: 0.03) segments differed from the amplitude in the first (Seg 1, mean: 0.44 μV , SEM: 0.02) or second segments (Seg 2, mean: 0.44 μV , SEM: 0.02). However, we found no main effect of exposure or exposure and segments interaction on these frequency bands.

In the third analysis, no effects of gender were found of Wi-Fi exposure in any of the tested frequency bands. However, amplitudes differed in the beta1 ($F(1,23)=4.392$, $p<0.05$, partial eta-squared=0.16) and beta2 ($F(1,23)=8.607$, $p<0.01$, partial eta-squared=0.27) independent from the RF-EMF exposure in every block.

4.3. Effects of Wi-Fi exposure on psychomotor vigilance task, subjective fatigue, attention and motivation

Results of the first analysis of PVT generally suggest performance was compromised as a function of time spent on the task. More specifically, impaired performance with increasing time-on-task was indicated by the significant main effect of block (mean RT: $F(2,36)=6.62$, $p<0.01$, partial eta-squared=0.27; 1/RT: $F(2,36)=7.85$, $p<0.01$, partial eta-squared=0.30; fastest RT: $F(2,36)=5.34$, $p<0.05$, partial eta-squared=0.23) and the significant main effect of interval (mean RT: $F(2,36)=18.99$, $p<0.001$, partial eta-squared=0.51; 1/RT: $F(2,36)=20.17$, $p<0.001$, partial eta-squared=0.53; Lapses: $F(2,36)=4.88$, $p<0.05$, partial eta-squared=0.21). Importantly, the type of exposure was not found to modulate the participants' performance for any performance measures.

In the second analysis, no effect of Wi-Fi exposure was found on gender as a between-subject factor.

The third analysis, except for the slowest RTs, Variability and Lapses, revealed significantly improved performance in the post-exposure block (Block IV) when compared to the last exposure block (Block III) (mean RT: $F(1,18)=5.04$, $p<0.05$, partial eta-squared=0.22; 1/RT: $F(1,18)=10.69$, $p<0.05$, partial eta-squared=0.37; fastest RT: $F(1,18)=10.45$, $p<0.01$, partial eta-squared=0.36). The change in performance from Block III to the Post-exposure block was not modulated by the type of exposure, and Exposure and Block interaction did not reach statistical significance for either of the performance measures. It is suggested that the improved performance in Block IV was caused by the longer (5+20 min) resting brake.

Finally, the analysis of the subjective fatigue (VAS) ratings yielded a significant increase in the participants' subjective fatigue over the course of the experiment (Block: $F(3,54)=20.89$, $p<0.00$, partial eta-squared=0.54). We found significantly decreased levels of motivation (Block: $F(3,54)=9.42$, $p<0.00$, partial eta-squared=0.34) and attention (Block: $F(2,36)=7.55$, $p<0.00$, partial eta-squared=0.3) during the process. However, participants reported similar fatigue, motivation and attention levels in the genuine Wi-Fi vs. sham exposure conditions as indicated by the non-significant main effect of the type of exposure.

5. Summary

In addition to natural background radiation, exposure to the man-made environmental electromagnetic (EM) energy including microwaves and radio waves has dramatically increased in the recent decades. Most of the exposure is derived from mobile communication (MC) technology. Although all MC device operate at EM energy levels that cannot disrupt chemical bonds, the non-ionizing radiation emitted by them may interfere with neurocognitive processes in the human brain. As no attempts has been done before to analyze these effects prior to the recent rapid proliferation of MC technology, therefore revealing are urgent need for the fine dissection of any possible interactions of MC derived EM with the living organisms. Biological effects of EM energy emitted by GSM and UMTS systems are intensively studied, nevertheless, the research of EM radiation generated by WLAN devices with similar parameters has just begun. Therefore, we aimed to build an experimental system, which mimics the features of EM radiation emitted by commercially available WLAN devices and which enables us to probe a model under highly regulated and safe laboratory circumstances. As the first step, a unique WLAN device was designed with precise dosimetry on free-field measurements and computational estimation of SAR, substantially described with heuristic characterization method, with stable exposure, and with peak SAR values below the international guidelines. Next, the effects of a 60-min irradiation [2.4 GHz, channel 9 (2452 MHz), 100 mW Wi-Fi in standard IEEE 802.11 b/g mode] were investigated on spontaneous awake electroencephalographic (sEEG) or on sustained attention. The latter was measured using a computerized version of the psychomotor vigilance test (PVT). Although the method applied in our study was robust enough to evoke changes, our results consistent with earlier studies clearly showed that an acute, 60-min single dose Wi-Fi exposure with the usual output power affects neither the oscillatory brain activity (assessed by sEEG) nor the basic neurocognitive processes of the human brain (assessed by PVT). However, it is important to point out, that the current research related to cognitive effects of GSM, UMTS or Wi-Fi technologies provides controversial, sometimes opposing results which can be explained by the modulation-specific effects of the different EM fields. Thus, to offer a conclusive result in respect of the neurocognitive effects of Wi-Fi radiation, the present results prompt further studies by using n and ac modes of IEEE 802.11 WLAN standard and by applying various signal-modulation scenarios.

6. Bibliography

- Aitken, R. C. (1969). Measurement of feelings using visual analogue scales. *Proc R Soc Med*, 62(10), 989-993.
- Banaceur, S., Banasr, S., Sakly, M., Abdelmelek, H. (2013). Whole body exposure to 2.4 GHz WIFI signals: effects on cognitive impairment in adult triple transgenic mouse models of Alzheimer's disease (3xTg-AD). *Behav Brain Res*, 240, 197-201.
- Borbely, A. A., Huber, R., Graf, T., Fuchs, B., Gallmann, E., Achermann, P. (1999). Pulsed high-frequency electromagnetic field affects human sleep and sleep electroencephalogram. *Neurosci Lett*, 275(3), 207-210.
- Celik, O., Kahya, M. C., Naziroglu, M. (2016). Oxidative stress of brain and liver is increased by Wi-Fi (2.45GHz) exposure of rats during pregnancy and the development of newborns. *J Chem Neuroanat*, 75(Pt B), 134-139.
- Christ, A., Kainz, W., Hahn, E. G., Honegger, K., Zefferer, M., Neufeld, E., Rascher, W., Janka, R., Bautz, W., Chen, J., Kiefer, B., Schmitt, P., Hollenbach, H. P., Shen, J., Oberle, M., Szczerba, D., Kam, A., Guag, J. W., Kuster, N. (2010). The Virtual Family-development of surface-based anatomical models of two adults and two children for dosimetric simulations. *Phys Med Biol*, 55(2), N23-38.
- Croft, R. J., Leung, S., McKenzie, R. J., Loughran, S. P., Iskra, S., Hamblin, D. L., Cooper, N. R. (2010). Effects of 2G and 3G mobile phones on human alpha rhythms: Resting EEG in adolescents, young adults, and the elderly. *Bioelectromagnetics*, 31(6), 434-444.
- Curcio, G., Ferrara, M., Moroni, F., D'Inzeo, G., Bertini, M., De Gennaro, L. (2005). Is the brain influenced by a phone call? An EEG study of resting wakefulness. *Neurosci Res*, 53(3), 265-270.
- Edelstyn, N., Oldershaw, A. (2002). The acute effects of exposure to the electromagnetic field emitted by mobile phones on human attention. *Neuroreport*, 13(1), 119-121.
- EFHRAN. (2012). European Health Risk Assessment Network on EMF Exposure. Report on risk analysis of human exposure to electromagnetic fields [Internet]. *Letöltve: 2017. június. 23. Link: http://efhran.polimi.it/docs/D2_Finalversion_oct2012.pdf*.
- Findlay, R. P., Dimbylow, P. J. (2010). SAR in a child voxel phantom from exposure to wireless computer networks (Wi-Fi). *Phys Med Biol*, 55(15), N405-411.

- Fiocchi, S., Parazzini, M., Liorni, I., Samaras, T., Ravazzani, P. (2014). Temperature increase in the fetus exposed to UHF RFID readers. *IEEE Trans Biomed Eng*, 61(7), 2011-2019.
- Gumral, N., Naziroglu, M., Koyu, A., Ongel, K., Celik, O., Saygin, M., Kahriman, M., Caliskan, S., Kayan, M., Gencel, O., Flores-Arce, M. F. (2009). Effects of selenium and L-carnitine on oxidative stress in blood of rat induced by 2.45-GHz radiation from wireless devices. *Biol Trace Elem Res*, 132(1-3), 153-163.
- Haarala, C., Bjornberg, L., Ek, M., Laine, M., Revonsuo, A., Koivisto, M., Hamalainen, H. (2003). Effect of a 902 MHz electromagnetic field emitted by mobile phones on human cognitive function: A replication study. *Bioelectromagnetics*, 24(4), 283-288.
- Haarala, C., Ek, M., Bjornberg, L., Laine, M., Revonsuo, A., Koivisto, M., Hamalainen, H. (2004). 902 MHz mobile phone does not affect short term memory in humans. *Bioelectromagnetics*, 25(6), 452-456.
- Haarala, C., Bergman, M., Laine, M., Revonsuo, A., Koivisto, M., Hamalainen, H. (2005). Electromagnetic field emitted by 902 MHz mobile phones shows no effects on children's cognitive function. *Bioelectromagnetics*, Suppl 7, S144-150.
- Haarala, C., Takio, F., Rintee, T., Laine, M., Koivisto, M., Revonsuo, A., Hamalainen, H. (2007). Pulsed and continuous wave mobile phone exposure over left versus right hemisphere: effects on human cognitive function. *Bioelectromagnetics*, 28(4), 289-295.
- Hassanshahi, A., Shafeie, S. A., Fatemi, I., Hassanshahi, E., Allahtavakoli, M., Shabani, M., Roohbakhsh, A., Shamsizadeh, A. (2017). The effect of Wi-Fi electromagnetic waves in unimodal and multimodal object recognition tasks in male rats. *Neurol Sci*, 38(6), 1069-1076.
- Hietanen, M., Kovalala, T., Hamalainen, A. M. (2000). Human brain activity during exposure to radiofrequency fields emitted by cellular phones. *Scand J Work Environ Health*, 26(2), 87-92.
- Huber, R., Treyer, V., Borbely, A. A., Schuderer, J., Gottselig, J. M., Landolt, H. P., Werth, E., Berthold, T., Kuster, N., Buck, A., Achermann, P. (2002). Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. *J Sleep Res*, 11(4), 289-295.
- IARC. (2011). IARC Report to the Union for International Cancer Control (UICC) on the Interphone Study [Internet]. *Letöltve: 2017. július. 15. Link: http://interphone.iarc.fr/UICC_Report_Final_03102011.pdf*.

- Juutilainen, J., Hoyto, A., Kumlin, T., Naarala, J. (2011). Review of possible modulation-dependent biological effects of radiofrequency fields. *Bioelectromagnetics*, 32(7), 511-534.
- Kleinlogel, H., Dierks, T., Koenig, T., Lehmann, H., Minder, A., Berz, R. (2008). Effects of weak mobile phone - electromagnetic fields (GSM, UMTS) on event related potentials and cognitive functions. *Bioelectromagnetics*, 29(6), 488-497.
- Koivisto, M., Krause, C. M., Revonsuo, A., Laine, M., Hamalainen, H. (2000a). The effects of electromagnetic field emitted by GSM phones on working memory. *Neuroreport*, 11(8), 1641-1643.
- Koivisto, M., Revonsuo, A., Krause, C., Haarala, C., Sillanmaki, L., Laine, M., Hamalainen, H. (2000b). Effects of 902 MHz electromagnetic field emitted by cellular telephones on response times in humans. *Neuroreport*, 11(2), 413-415.
- Kwon, M. S., Hamalainen, H. (2011). Effects of mobile phone electromagnetic fields: critical evaluation of behavioral and neurophysiological studies. *Bioelectromagnetics*, 32(4), 253-272.
- Leung, S., Croft, R. J., McKenzie, R. J., Iskra, S., Silber, B., Cooper, N. R., O'Neill, B., Cropley, V., Diaz-Trujillo, A., Hamblin, D., Simpson, D. (2011). Effects of 2G and 3G mobile phones on performance and electrophysiology in adolescents, young adults and older adults. *Clin Neurophysiol*, 122(11), 2203-2216.
- Maganioti, A. E., Papageorgiou, C. C., Hountala, C. D., Kyprianou, M. A., Rabavilas, A. D., Papadimitriou, G. N., Capsalis, C. N. (2010). Wi-Fi electromagnetic fields exert gender related alterations on EEG [Internet]. *ResearchGate, Letöltve: 2017. július 15.* Link: https://www.researchgate.net/publication/267816859_WI-FI_ELECTROMAGNETIC_FIELDS_EXERT_GENDER_RELATED_ALTERATIONS_ON_EEG.
- Martinez-Burdalo, M., Martin, A., Sanchis, A., Villar, R. (2009). FDTD assessment of human exposure to electromagnetic fields from WiFi and bluetooth devices in some operating situations. *Bioelectromagnetics*, 30(2), 142-151.
- Naziroglu, M., Gumral, N. (2009). Modulator effects of L-carnitine and selenium on wireless devices (2.45 GHz)-induced oxidative stress and electroencephalography records in brain of rat. *Int J Radiat Biol*, 85(8), 680-689.
- Mueller, S. T. and Piper, B. J. (2014). The Psychology Experiment Building Language (PEBL) and PEBL Test Battery. *J Neurosci Methods*, 222, 250-259.

- Papageorgiou, C. C., Hountala, C. D., Maganioti, A. E., Kyprianou, M. A., Rabavilas, A. D., Papadimitriou, G. N., Capsalis, C. N. (2011). Effects of wi-fi signals on the p300 component of event-related potentials during an auditory hearing task. *J Integr Neurosci*, 10(2), 189-202.
- Paulraj, R., Behari, J. (2006). Protein kinase C activity in developing rat brain cells exposed to 2.45 GHz radiation. *Electromagn Biol Med*, 25(1), 61-70.
- Preece, A. W., Iwi, G., Davies-Smith, A., Wesnes, K., Butler, S., Lim, E., Varey, A. (1999). Effect of a 915-MHz simulated mobile phone signal on cognitive function in man. *Int J Radiat Biol*, 75(4), 447-456.
- Preece, A. W., Goodfellow, S., Wright, M. G., Butler, S. R., Dunn, E. J., Johnson, Y., Manktelow, T. C., Wesnes, K. (2005). Effect of 902 MHz mobile phone transmission on cognitive function in children. *Bioelectromagnetics, Suppl 7*, S138-143.
- Regel, S. J., Gottselig, J. M., Schuderer, J., Tinguely, G., Retey, J. V., Kuster, N., Landolt, H. P., Achermann, P. (2007). Pulsed radio frequency radiation affects cognitive performance and the waking electroencephalogram. *Neuroreport*, 18(8), 803-807.
- Reiser, H., Dimpfel, W., Schober, F. (1995). The influence of electromagnetic fields on human brain activity. *Eur J Med Res*, 1(1), 27-32.
- Röschke, J., Mann, K. (1997). No short-term effects of digital mobile radio telephone on the awake human electroencephalogram. *Bioelectromagnetics*, 18(2), 172-176.
- Schmid, G., Lager, D., Preiner, P., Uberbacher, R., Cecil, S. (2007). Exposure caused by wireless technologies used for short-range indoor communication in homes and offices. *Radiat Prot Dosim*, 124(1), 58-62.
- Shekoohi-Shooli, F., Mortazavi, S. M., Shojaei-Fard, M. B., Nematollahi, S., Tayebi, M. (2016). Evaluation of the protective role of vitamin C on the metabolic and enzymatic activities of the liver in the male rats after exposure to 2.45 GHz of Wi-Fi routers. *J Biomed Phys Eng*, 6(3), 157-164.
- Stefanics, G., Thuróczy, G., Kellényi, L., Hernádi, I. (2008). Effects of twenty-minute 3G mobile phone irradiation on event related potential components and early gamma synchronization in auditory oddball paradigm. *Neuroscience*, 157(2), 453-462.
- Trunk, A., Stefanics, G., Zentai, N., Kovács-Bálint, Z., Thuróczy, G., Hernádi, I. (2013). No effects of a single 3G UMTS mobile phone exposure on spontaneous EEG activity, ERP correlates, and automatic deviance detection. *Bioelectromagnetics*, 34(1), 31-42.

- Trunk, A., Stefanics, G., Zentai, N., Bacskay, I., Felinger, A., Thuróczy, G., Hernádi, I. (2014). Lack of interaction between concurrent caffeine and mobile phone exposure on visual target detection: an ERP study. *Pharmacol Biochem Behav*, 124, 412-420.
- Trunk, A., Stefanics, G., Zentai, N., Bacskay, I., Felinger, A., Thuróczy, G., Hernádi, I. (2015). Effects of concurrent caffeine and mobile phone exposure on local target probability processing in the human brain. *Sci Rep*, 5, 14434.
- van Rongen, E., Croft, R., Juutilainen, J., Lagroye, I., Miyakoshi, J., Saunders, R., de Seze, R., Tenforde, T., Verschaeve, L., Veyret, B., Xu, Z. (2009). Effects of radiofrequency electromagnetic fields on the human nervous system. *J Toxicol Environ Health B Crit Rev*, 12(8), 572-597.
- Wang, J., Fujiwara, O. (2005). EM interaction between a 5 GHz band antenna mounted PC and a realistic human body model. *IEICE Trans Comm*, E88-B(6), 2604-2608.
- WHO. (2011). IARC classifies radiofrequency electromagnetic fields as possibly carcinogenic to humans. [Internet]. *Letöltve: 2017. június. 23.* Link: http://www.iarc.fr/en/media-centre/pr/2011/pdfs/pr208_E.pdf.
- Wiat, J., Hadjem, A., Wong, M. F., Bloch, I. (2008). Analysis of RF exposure in the head tissues of children and adults. *Phys Med Biol*, 53(13), 3681-3695.

7. Publications

Publications related to the thesis:

1. **Zentai, N.**, Fiocchi, S., Parazzini, M., Trunk, A., Juhász, P., Ravazzani, P., Hernádi, I., Thuróczy, Gy. (2015). Characterization and evaluation of a commercial WLAN system for human provocation studies. *Biomed Res Internat*, Vol. 2015: Paper 289152. 10 p. **IF: 2,706**
2. **Zentai, N.**, Csathó, Á., Trunk, A., Fiocchi, S., Parazzini, M., Ravazzani, P., Thuróczy, Gy., Hernádi, I. (2015). No effects of acute exposure to Wi-Fi electromagnetic fields on spontaneous EEG activity and psychomotor vigilance in healthy human volunteers. *Rad Res*, 184(6):568-577. **IF: 2,539**

Posters related to the thesis:

1. **Zentai, N.**, Trunk, A., Csathó, Á., Juhász, P., Fiocchi, S., Thuróczy, Gy., Hernádi, I. (2014). Investigation of possible cognitive effects of Wi-Fi electromagnetic fields assessed by spontaneous EEG and psychomotor vigilance measures. 9th FENS Forum of Neuroscience, Milan, Italy. (Poster presentation, abstract)
2. **Zentai, N.**, Csathó, Á., Trunk, A., Hernádi, I. (2013). No effects of 60 minute Wi-Fi electromagnetic field exposure on human cognitive performance in a psychomotor vigilance task. II. Interdiszciplináris Doktorandusz Konferencia, Pécs, Magyarország. (Poster presentation, abstract)
3. **Zentai, N.**, Csathó, Á., Trunk, A., Hernádi, I. (2013). Investigation of possible effects of 60 minute Wi-Fi electromagnetic field exposure on human cognitive performance in a psychomotor vigilance task. 14th Conference of the Hungarian Neuroscience Society (MITT), Budapest, Hungary. (Poster presentation, abstract)
4. **Zentai, N.**, Trunk, A., Juhász, P., Thuróczy, Gy., Hernádi, I. (2012). The effects of 60 minute Wi-Fi electromagnetic field exposure on spontaneous EEG activity of healthy human volunteers. 8th FENS Forum of European Neuroscience, Barcelona, Spain. (Poster presentation, abstract)

5. **Zentai, N.**, Trunk, A., Stefanics, G., Hernádi, I. (2012). The effect of 60 minute Wi-Fi electromagnetic field exposure on skin surface temperature and spontaneous EEG activity of healthy human volunteers. IBRO International Workshop, Szeged, Hungary. (Poster presentation, abstract)
6. **Zentai, N.**, Trunk, A., Juhász, P., Stefanics, G., Thuróczy, G., Hernádi, I. (2011). The effect of a single 60 minute Wi-Fi electromagnetic field exposure on spontaneous EEG activity of healthy human volunteers. 13th Conference of the Hungarian Neuroscience Society (MITT), Budapest, Hungary. (Poster presentation, abstract)
7. **Zentai, N.**, Juhász, P., Trunk, A., Thuróczy, G., Hernádi, I. (2011). Evaluation of WLAN exposure system constructed from modular, commercially available parts for biological experimentation. 10th International Conference of the European Bioelectromagnetics Association (EBEA), Roma, Italy. (Poster presentation, abstract)
8. Fiocchi, S., Parazzini, M., Liorni, I., **Zentai, N.**, Guadagnin, V., Thuróczy, Gy., Ravazzani, P., (2014). SAR assessment in different models and positions from Wireless Local Area Networks (WLAN) system. Joint Annual Meeting of the Bioelectromagnetics Society (BEMS) and European Bioelectromagnetics Association (EBEA), Cape Town, South Africa. (Poster presentation, abstract)

Publications not related to the thesis:

1. Trunk, A., Stefanics G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy Gy., Hernádi, I. (2015). Effects of concurrent caffeine and mobile phone exposure on local target probability processing in the human brain. *Sci Rep* 5, Article number: 14434. **IF: 4,259**
2. Trunk, A., Stefanics, G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2014). Lack of interaction between concurrent caffeine and mobile phone exposure on visual target detection: An ERP study. *Pharmacol Biochem Behav*, 124: pp. 412-420. **IF: 2,820**
3. Trunk, A., Stefanics, G., **Zentai, N.**, Kovács-Bálint, Zs., Thuróczy, G., Hernádi, I. (2013). No effects of a single 3G UMTS mobile phone exposure on spontaneous EEG activity, ERP correlates, and automatic deviance detection. *Bioelectromagnetics*, 34:(1) pp. 31-42. **IF: 1,859**

Posters not related to the thesis:

1. Horváth, Z., **Zentai, N.**, Jenák, I. (2017). Indoor autonomous drone development. 13th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery (ICNC-FSKD). Guilin, China. (Presentation, conference article)
2. Botzheim, L., Mravcsik, M., **Zentai, N.**, Malik, S., Laczkó, J. (2017). Body position affects muscle activity variances in the non-dominant arm during arm cycling. Neuroscience (SfN), Washington, USA. (Poster presentation, abstract)
3. **Zentai, N.**, Mravcsik, M., Botzheim, L., Malik, Sz., Laczkó J. (2016). Kinematic stability of arm cycling by the dominant and nondominant arm. 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Orlando, USA. (Poster presentation, abstract)
4. Botzheim, L., Malik, Sz., Mravcsik, M., **Zentai, N.**, Laczkó, J. (2016). Comparison of muscle activities during arm cycling in horizontal and vertical planes. V. International Scientific Conference - Motor Control, Wisła, Poland. (Poster presentation, abstract)
5. Mravcsik, M., **Zentai, N.**, Botzheim, L., Laczkó, J. (2016). Unimanual versus bimanual arm cycling movements – muscle activity variances. Neuroscience (SfN), San Diego, USA. (Poster presentation, abstract)
6. Mravcsik M., Botzheim L., **Zentai N.**, Laczkó J. (2015). Stabilization of arm configuration and muscle activity patterns during cycling arm movements against external resistances. Progress in Motor Control X. Conference, Budapest, Hungary. (Poster presentation, abstract)
7. Mravcsik, M., Botzheim, L., **Zentai N.**, Laczkó J. (2015). Variances of joint configuration and muscle activity patterns during arm cycling against external resistances. Neuroscience (SfN), Chicago, USA. (Poster presentation, abstract)
8. Trunk, A., Stefanics, G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2014). Investigation of possible synergistic effects of caffeine intake and UMTS mobile phone-like exposure on human visual attention. 7th COURSE: “Biological effects of combined exposures to EMF and other chemical and physical agents”, Erice, Italy. (Poster presentation, abstract)
9. Trunk, A., **Zentai, N.**, Csathó, Á., Gács, B., Hernádi, I. (2014). Modulatory effects of

- caffeine on human visual attention indexed by the N200 event related potential. 9th Forum of Neuroscience (FENS), Milan, Italy. (Poster presentation, abstract)
10. Vecsei, Zs., **Zentai, N.**, Thuróczy, Gy., Hernádi, I. (2014). Twenty-Minute UMTS mobile phone exposure does not affect cognitive performance of young healthy volunteers evaluated on the basis of the Stroop color word test. International Brain Research Organization Workshop (IBRO), Debrecen, Hungary. (Poster presentation, abstract)
 11. Trunk, A., **Zentai, N.**, Csathó, Á., Hernádi, I. (2014). Koffein vizuális figyelmet javító hatása: eseményhez kötött potenciál vizsgálat. A Magyar Kísérletes és Klinikai Farmakológiai Társaság Experimentális Farmakológiai szekciójának VIII. szimpóziuma és az MBKE Gyógyszerbiokémiai Szakosztály XXVIII. Munkaértekezlete, Velence, Magyarország. (Poszter előadás, absztrakt)
 12. Trunk, A., **Zentai, N.**, Stefanics, G., Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2013). No combined effects of caffeine and 3G mobile phone exposure on predictive coding in the human brain. 14th Conference of the Hungarian Neuroscience Society (MITT), Budapest, Hungary. (Poster presentation, abstract)
 13. Trunk, A., Stefanics, G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2013). No evidence of interactions between caffeine intake and 3G mobile phone exposure on target expectancy in the human brain. II. Interdiszciplináris Doktorandusz Konferencia, Pécs, Hungary. (Poster presentation, abstract)
 14. Trunk, A., Stefanics, G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2013). Investigation of possible synergistic effects of caffeine intake and UMTS mobile phone-like exposure on predictive coding in the human brain. 11th International Conference of the European Bioelectromanetics Association (EBEA), Thessaloniki, Greece. (Poster presentation, abstract)
 15. Vecsei, Zs., **Zentai, N.**, Juhász, P., Thuróczy, Gy. (2013). Possible effects of 20 min LTE mobile phone exposure on cognitive performance assessed by Stroop test in young healthy human volunteers. 11th International Conference of the European Bioelectromanetics Association (EBEA), Thessaloniki, Greece. (Poster presentation, abstract)
 16. Vecsei, Zs., Báló, V., **Zentai, N.**, Juhász, P., Thuróczy, Gy., Hernádi, I. (2013). Investigation of putative effects induced by acute LTE mobile phone-like exposure on cognitive

performance of healthy volunteers. II. Interdiszciplináris Doktorandusz Konferencia, Pécs, Hungary. (Poster presentation, abstract)

17. Bacskay, I., Trunk, A., **Zentai, N.**, Thuróczy, Gy., Hernádi, I., Felinger, A. (2012). Új generációs mobiltelefon sugárzás hatása a koffein nyálba történő kiválasztására emberben. Magyar Elválasztástudományi Vándorgyűlés, Hajdúszoboszló, Magyarország. (Poszter előadás, absztrakt)
18. Trunk, A., Stefanics, G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2012). Novel experimental design to test potential synergistic effects of caffeine and 3G mobile phone exposure on human visual evoked potentials. 8th FENS Forum of European Neuroscience, Barcelona, Spain. (Poster presentation, abstract)
19. Trunk, A., Stefanics, G., **Zentai, N.**, Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2012). Possible synergistic effects of caffeine and 3G mobile phone exposure on human reaction time and visual event-related potentials. IBRO International Workshop, Szeged, Hungary. (Poster presentation, abstract)
20. Trunk, A., **Zentai, N.**, Stefanics, G., Bacskay, I., Felinger, A., Thuróczy, Gy., Hernádi, I. (2012). Combined effects of caffeine and 3G mobile phone exposure on predictive coding in the human brain. ERNI-HSF. Brain oscillations in health and disease, Budapest, Hungary. (Poster presentation, abstract)
21. Trunk, A., Stefanics, G., **Zentai, N.**, Kovács-Bálint, Zs., Thuróczy, G., Hernádi, I. (2011). The effect of a single 30 minute long 3G EMF exposure on auditory evoked potentials, automatic deviance detection and spontaneous EEG (sEEG). 13th Conference of the Hungarian Neuroscience Society (MITT), Budapest, Hungary. (Poster presentation, abstract)
22. Trunk, A., Stefanics, G., **Zentai, N.**, Hernádi, I. (2011). A koffein hatása az emberi auditoros és vizuális eseményhez kötött kiváltott potenciálokra ingerdiszkriminációs paradigmában. Magyar Farmakológus Anatómus Mikrocirkulációs Élettani Társaságok Közös Tudományos Konferenciája (FAME), Pécs, Magyarország. (Poszter előadás, absztrakt)

Cumulative impact factor of publications: 14.183

Number of independent citations: 59