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Health Effects of 5G Base Station Exposure: A Systematic Review

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ABSTRACT The Fifth Generation (5G) communication technology will deliver faster data speeds and support numerous new applications such as virtual and augmented reality. The additional need for a larger number of 5G base stations has sparked widespread public concerns about their possible negative health impacts. This review analyzes the latest research on electromagnetic exposure on humans, with particular attention to its effect on cognitive performance, well-being, physiological parameters, and Electroencephalography (EEG). While most of their results indicated no changes in cognitive function, physiological parameters, or overall well-being, the strength of the EEG alpha wave is noticed to vary depending on various aspects of cognitive functions. However, the available studies have not investigated the health effects resulting from exposure from the 5G mobile phone and base station antennas from 700 MHz to 30 GHz on the cognitive performance, well-being subjective symptoms, human physiological parameters, and EEG of adults. There is a need for such research regarding this current emerging technology. Such studies are significant in determining whether 5G technology is indeed safe for humans.

INDEX TERMS Radiofrequency electromagnetic fields, public health, 5G exposure, bioelectromagnetics, base station, mobile phones, antenna and propagation, cognitive function, electroencephalography, electromagnetic hypersensitivity, well-being, human studies, health.

I. INTRODUCTION

The introduction of the Global System for Mobile Communication (GSM) in the 1990's, Universal Mobile Telecommunication System (UMTS) in 2000, Long Term Evolution (LTE) in 2010 and the 5G mobile networks in 2020 have dramatically increased the use of Mobile Phones (MPs). Mobile services will be used by over three-quarters of the world's population, or 5.7 billion people. 5G will offer needed wireless infrastructure to keep up with the constant increase in data consumption and will satisfy the demands by innovative applications such as networked and autonomous automobiles, smart factories, and cities, etc. Revolutionary technologies such as beamforming and Massive Multiple-Input Multiple-Output (MaMIMO), besides innovative new radio coding software will enable 5G to support a considerably larger number of terminals (up to one million per square kilometer) with much greater data speeds (peak rate up to 20 Gbps), extremely low latency (no more than 1 ms), and exceptionally high dependability (99.999%). This provide users with a high quality of service while also enabling extremely dependable enormous communication between devices [1].

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In comparison to Second through Fourth Generation (2G to 4G) mobile technologies (such as GSM, UMTS, and LTE), the 5G New Radio (NR) technology utilize a huge span of spectrum which are divided into two broad ranges: the first spanning from 410 MHz to 7.125 GHz (known as the 'sub-6 GHz' frequency range), and the second from 24.25 GHz to 52.6 GHz (known as the millimeter-wave 'mmWave' frequency range). Furthermore, MaMIMO will support up to hundreds of antennas to allow many users to share the same time-frequency slot, increasing network capacity and improving transmission range while reducing power consumption [2]. The signal at the receiver will be one of the primary technological advancements improved in 5G NR [3]. MaMIMO system employs many transmit antennas at the Base Station (BS) as this is enables them to recover information even with a poor Signal-to-Noise-Ratio (SNR) and highly noisy channel estimates. At least an order of magnitude of additional antennas is expected in MaMIMO systems compared to existing cellular systems.

Electromagnetic Fields (EMF) exposure potentially affects the human body, including 'heating' of the skin. The temperature of a skin's outer surface is usually between 30°C and 35°C. The pain detection threshold temperature for human skin is around 43°C [4] and any temperature surpassing it can cause a long-term injury. Heating is a significant influence since it can result in cell damage and protein induction. High-frequency EMF is also known to influence the sweat glands (which may serve as helical antennas), peripheral nerves, the eyes and the testes, and may have indirect effects on other organs in the body [5]. The Federal Communications Commission (FCC) of the United States (US) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) established recommendations for the maximum quantity of EMF radiation that may be administered to a person's body. It is recommended by the FCC's guideline that the Specific Absorption Rate (SAR) is averaged over 1 gram (g) of tissue, whereas the ICNIRP's guideline is averaged over 10g. Recommendation by the FCC looks to be stricter, whereas 2-3 times energy absorption is permitted by the ICNIRP. In addition to that, the US Food and Drug Administration (FDA) states that the current knowledge of the negative effects of EMF emissions on human health is insufficient to determine whether exposure to the emissions is safe or not, and that more research is needed to fill in the gaps in the literature on human health safety in wireless systems use [6]. Meanwhile, the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) categorizes EMF exposure as a "possibly carcinogenic to humans" (Group 2B) [7]. The ICNIRP exposure recommendations [8] establish a maximum power density of 10 W/m^2 for the general population between 10 GHz and 300 GHz, measured as an average across any 20 cm^2 of exposed area. Moreover, the spatial maximum power density averaged over any 1 cm^2 shall not exceed 200 W/m^2. The uncontrolled power density exposure limit for FCC between 6 GHz to 100 GHz is also 10 W/m^2, which in general is to be considered as a spatial peak value [4], [9]. However, spatial peak is not a well-defined quantity, and the answer obtained will be dependent on the method used to measure exposure. Measurements will be averaged across the probe dimensions, and a suitable sample density will be required for calculations. Between 3 GHz to 100 GHz, the IEEE general public basic restriction on power density is 10 W/m^2 [10]. In the frequency range between 3 GHz to 30 GHz, the power density is to be spatially averaged over any contiguous area corresponding to 100λ^2, where λ is the free space wavelength of the Radiofrequency (RF) field. IEEE also specifies the maximum spatial peak power densities of 18.56$f^{0.699}$ W/m^2 at frequencies between 3 GHz and 30 GHz, where f is the frequency in GHz. However, IEEE specifies neither average area nor spatial sampling density for this limitation, and measurements using a minimum spatial sampling density of four samples per wavelength was performed in [6].

The accelerating deployment of telecommunication towers and base stations raises public concerns about possible health effects of the radiation coming from those structures in the recent few years. In Malaysia, for example, demonstrations and complaints have been lodged by the public against the construction of telecommunication tower in their residential areas [11], [12]. Concerns regarding the harmful effects of radio frequencies on human health might potentially be a stumbling block to broaden 5G infrastructure deployment. The mmWave spectrum will be utilized to build a dense network of small picocells, resulting in the installation of many new radio transmitters [1]. The Engineering & Technology (E&T) Magazine reported recently that the UK government has published a guide for the public about 5G networks due to the increase of 5G conspiracy theories on social media platforms, including that the COVID-19 pandemic could be linked to the new networks in some way. The misinformation spread quickly and led to numerous accounts of people vandalizing 5G masts over this concern [13].

The necessity of a very high data rate in 5G necessitates an increase in signal power received at the user's end, possibly increasing the electromagnetic radiation inflicted on the user in the vicinity [14]–[16]. Furthermore, three features of 5G which may potentially increase human EMF exposure further is explained as follows. Firstly, 5G aims to operate at higher frequencies (e.g., 28, 60, and 70 GHz) besides the existing lower frequency bands for cellular communications. However, as the frequency of EMFs increases, so does the rate of signal absorption into the human skin. Secondly, the variation in cell size between mmWave 5G, 4G, and 3.5G is a key suspect in increasing the level of human EMF exposure prior to the deployment of 4G, the 3GPP released 3.9G. There will be more transmitters in operation in the vicinity of the community due to the use of small cells in mmWave 5G. These BSs service smaller geographic regions and are consequently closer to human users. Among the three technologies, 5G communication systems feature the smallest cell diameter (200 m) with an Inter-Site Distance (ISD) of 100 m. This distance is also the maximum distance between a user and a mmWave 5G BS. Finally, in 5G, directed beams are needed to solve the faster signal power attenuation due to higher operating frequencies. It is important to note that the major reason for implementing multiple-antenna systems is to enhance antenna gain. Due to the larger concentration of electromagnetic radiation, EMF has a better chance of penetrating deeper into a human body [17]. Most previous research have focused solely on the uplink, with little attention paid to EMF emissions generated by BSs in a 5G network, as illustrated in Figure 1. The uplink in 5G is described as the allocation of power resources among users via User Equipment (UE), i.e., MPs. Meanwhile, the downlink in 5G is defined as the power resource that is centralized inside the BSs. Due to the changes in coverage exposure area in mmWave 5G, the downlink may also pose a hazard to human health [18]. In summary, the changes due to the adoption of 5G mmWave are as follows:

i. increased carrier frequency operation
ii. reduction in cell size (resulting in an increase in the number of BSs)
iii. greater EMF energy concentration in an antenna beam

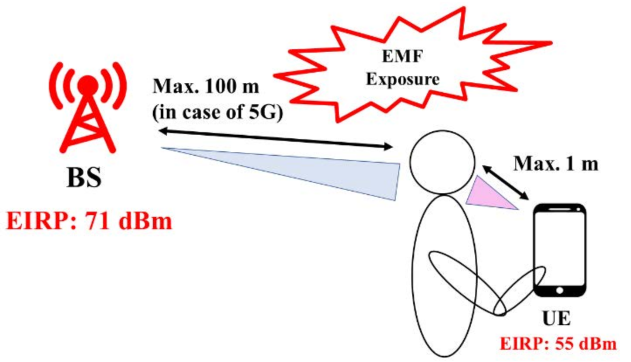

FIGURE 1. Comparison of uplink and downlink in 5G [18]. EIRP – Effective isotropic radiated power and UE – User equipment.

Various studies have reported the effects of Radiofrequency Electromagnetic Fields (RF-EMF) radiation on the cognitive performance, well-being subjective symptoms, human physiological parameters, and EEG. They are primarily focused on wireless communication devices such as BS antennas operating in different frequency bands [10], [19]–[23], MPs [17], [24]–[27], Wi-Fi [10], Terrestrial Trunked Radio (TETRA) BS [28] and portable TETRA handsets [29]. To date, it is unclear whether RF-EMF field emitted by MP BSs affects well-being in adults, as the results from the existing studies on this topic are inconsistent. The health effects of RF-EMF due to 5G frequencies were studied [30] from 6 to 100 GHz on in vivo and in vitro biological structures. However, to the best of our knowledge, none of previous reviews focused on the health effects resulting from exposure from the 5G MP and BS antennas from 700 MHz to 30 GHz on the cognitive performance, well-being subjective symptoms, human physiological parameters, and EEG of adults. Moreover, a recent study [18] highlighted that 5G radiation at 28 GHz may represent a hazard to human health, making such assessment urgently needed. This is significant in determining whether 5G technology is indeed safe for human.

II. LITERATURE SEARCH AND SELECTION METHODOLOGY

The literature search was performed in May 2021 using keywords related to RF-EMF such as 'radiofrequency', 'RF', 'electromagnetic field', 'EMF', 'mobile phone', 'cellular phone', '2G', '3G, '4G', 'GSM', 'UMTS', 'LTE'. Besides that, more specific terms related to 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'), cognitive performance (such as 'reaction time', 'RT', 'psychology'), well-being (such as 'subjective symptom', 'well-being symptoms', blood pressure', 'BP', 'heart rate', 'HR', body temperature', 'BT', 'Electromagnetic Hypersensitivity (EHS)', 'non-EHS'). Upon compilation of these literature, a pre-selection is performed based on the title and abstract of these English-language publications. Then, employing full text analysis, a more extensive examination of relevant papers was conducted, with studies chosen based on the following inclusion criteria:

- blind condition (single or double blind)/randomized/ balance study with a cross-over design,
- IEI-EMF reported symptoms (non-EHS or EHS subjects),
- physiological parameter (blood pressure, body temperature or heart rate),
- subjective symptoms (well-being or visual analog scales),
- cognitive performance as experimental approach,
- investigation of the EEG technique and waking spontaneous EEG,
- radiofrequency range related to BS and MP technologies,
- radiofrequency range related to 5G technologies.

As a result, 33 studies (ten for cognitive performance, 13 for well-being and physiological and ten for EEG) were selected for inclusion in this review. The next section explains the findings from the literatures, followed by an analysis and discussion of the previous findings. In the following sections, the experimental protocols, materials and methods of each selected study, and parameters will be compared and discussed in the final section. These include the volunteers' inclusion criteria and physiological measures, SAR, RF-EMF, exposure period, etc.

III. COGNITIVE PERFORMANCE

Healthy adult volunteers who described feeling a range of symptoms such as headaches in the proximity of RF sources were studied in terms of cognitive function. Many studies have examined how MPs radiation affects cognitive performance using behavioral metrics. They include response speed and accuracy in a variety of tasks, as shown in Table 1. For instance, Preece et al [31] tested the short-term and long-term memory, simple and choice response time, and sustained attention on $N = 36$ participants, yielding a total of 15 dependent variables. N is defined as number of volunteers/subjects. Using a single-blind, counterbalanced, randomized cross-over method, volunteers were exposed, or Sham exposed, to continuous or pulsed 915 MHz GSM-type transmissions for about 30 minutes. In the Choice Response Time (CRT) task, there was a statistically significant reduction in Reaction Time (RT) when exposed to the continuous signal. The impact was not followed by a decrease in response accuracy, indicating that it was not a speed-accuracy trade-off. Simple Response Times (SRTs) were unchanged, and word, number, and image recall, as well as spatial memory, were constant. Exposure to a pulsed GSM signal had no significant impact.

Koivisto et al [32] evaluated at 48 individuals and used a variety of cognitive tests. Volunteers were exposed or Sham-exposed to a 902 MHz GSM signal using a single blind counter-balanced crossover setup. In basic RT and Vigilance (VIG) activities, slower RTs were reported [33], similar with the reported findings in [32]. Furthermore, during exposure, the time required to complete a mental arithmetic, Subtraction Time (SUB) assignment was reduced. A second research used a similar experimental design to evaluate the effects of GSM RF on the execution of a task with varying working memory demand [33]. A statistically significant reduction of RT was reported when the memory load was particularly demanding. However, a similar attempt to validate and expand the findings of both investigations failed [32], [33].

Curcio *et al.* [34] studied a small number of volunteers ($N = 20$) using various cognitive tests in a double-blind counterbalanced crossover design. The subjects were tested on four cognitive tasks, i.e., an acoustic SRT task, a visual search task, an arithmetic descending SUB task, and an acoustic CRT task. The results indicated that both SRT and CRT were reduced during exposure to a 902 MHz GSM signal than Sham exposure. However, an attempt by the same research group to replicate and confirm the finding was not successful, as no significant effects in the same SRT task was observed (the CRT test was not performed) [35]. Other studies also have failed to detect significant effects of mobile phone and BS signal exposure on the cognitive performance of human. Cinel *et al.* [17] replicated the effect of GSM MPs on attention and memory functions presented earlier in [32], [33] with a larger sample size ($N = 168$). However, the effect of exposure on any of the six cognitive tests as those performed by [32], [33] was far from significant.

Sauter *et al.* [29] found no evidence of a detrimental impact of a short-term EMF-effect of a TETRA hand-held transmitter on the cognitive performance of healthy young males. Computer tests on three distinct elements of attention (i.e., divided attention, selective attention, VIG) and working memory were used to assess cognitive functions. Recently, Vecsei *et al.* [36] observed the short-term RF-EMF exposure from 3G and 4G MPs. Similarly, the Stroop test revealed that these signals had no effect on the cognitive functioning of executive function measurements, processing speed, or selective attention. Table 1 summarizes the studies investigating the effects of RF-EMF exposure on cognitive performance and findings in literature.

IV. ADULTS WITH EMF-ATTRIBUTED SYMPTOMS

Zwamborn *et al.* [37] first explored the subjective feelings and cognitive functions in a group of 36 people who claimed to have symptoms related to living near a GSM BS and a group of 36 healthy people in a research that used exposure comparable to that from a BS. As the groups differed in age and gender distribution, no comparisons could be conducted between categories; only within groups for periods with and without exposure could be performed. The individuals were exposed to a 1 V/m field at 900 and 1800 MHz (GSM signal), and 2100 MHz (UMTS signal). Using a double-blind design, each volunteer participated in three sessions, one of which was unexposed. Each exposure group had 24 individuals. Each session lasted 45 minutes, consisting of the exposure (during which cognitive skills were assessed), the questionnaire, and the break. The cognitive functions that were tested were RT, memory comparison, dual-tasking, selective visual attention, and filtering irrelevant information. A revised analysis of the data was provided in a report by the Netherlands Health Council (2004). With the cognitive function tests, only one statistically significant result was obtained in this reanalysis. UMTS exposure resulted in a higher completion rate of the memory comparison test in the control group without symptoms. This might be a coincidental impact. The findings in terms of symptoms have been explored in the subsection on electrosensitive persons.

The follow-up study by Regel *et al.* [19] solely evaluated the effect of the 2140 MHz UMTS BS-like RF signal (identical to that employed by [37]) on the well-being and cognitive functions in 33 EHS and 84 non-EHS subjects. Three experimental sessions were performed one week apart, with individuals randomly allocated to one of the six potential sequences of three exposure conditions, each lasting 45 minutes: 0 V/m (sham), 1 V/m (identical to that used by [37]), and 10 V/m (in order to assess any possible dose-response relationship). The study used a randomized crossover design and was double blinded. Cognitive performance was assessed using a SRT task, a 2-CRT task, the n-back task, and the visual selective attention task. The visual selective attention task was also used in [37]. There was no effect found from this study from any exposure level on the cognitive performance of the volunteers. Next, Eltiti *et al.* [21] evaluated the influence of GSM and UMTS BS signals on the cognitive performance, focusing on attention and memory. They also utilized a variety of cognitive assessments. In addition to the control group of volunteers, this study included self-reported sensitive subjects. This is to test the hypothesis that the self-reported sensitive group would have decreased cognitive functioning. The subjects were exposed to Sham or GSM and UMTS signals from a BS antenna using a double-blind, counterbalanced, randomized cross-over approach. Both exposure signals have power flux densities of 10 mW/m^2 over the radiating region. The findings revealed that neither GSM nor UMTS BS signals had any significant influence on the attention or memory functions.

Wallace *et al.* [28] studied the effect of TETRA BS signal to two group of subjects (EHS = 48 and non-EHS = 132). The authors [28] also found that TETRA BS signal did not affect the cognitive performance for neither non-EHS nor EHS volunteers. Neither group were able to detect the presence of a TETRA signal at rates greater than chance (50%). It was also discovered that the EHS patients' negative symptoms are caused by their fear of TETRA BSs rather than the low-level EMF exposure itself. In [22], Malek *et al.* also found no significant cognitive performance changes in both self-reported EHS and non-EHS groups when exposed to 2G and 3G MP BSs. In another recent study, van Moorselaar *et al.* [38] took a different approach in measuring the effects of RF-EMF exposure with personalized exposure setting at home involving 42 EHS subjects. A variety of RF-EMF types of exposure was emitted through their personal exposure units such as GSM 900, GSM 1800, cordless phone Digital European Cordless Telecommunications (DECT), UMTS and Wi-Fi 2.45 GHz signals. The authors concluded that during double-blinded testing, no participant was able to correctly identify when they were being exposed. This confirms the other findings that the RF-EMF exposure does not affect the symptoms reported by the EHS subjects. However, during follow-up sessions, EHS participants reported fewer symptoms compared to the symptoms reported before the exposure.

In a more recent study, Bogers *et al.* [23] observed the effects of continuous RF-EMF exposure from signals emulating GSM/UMTS BS, Wi-Fi and DECT. It was observed that Wi-Fi and GSM/UMTS BS exposures were associated with the self-declared symptoms by some of the EHS subjects. This finding contradicted against most of the findings from previous studies, which reported that there are no effects of RF-EMF exposure on the well-being of self-reported EHS individuals. Table 1 and 2 summarize the studies investigating the effects of RF-EMF exposure on cognitive performance, EMF perception and well-being of EHS subjects findings in literature.

V. WELL-BEING SUBJECTIVE SYMPTOMS

To further examine whether EMF exposure affects the behavior of human, many studies have investigated the second part of human behavioral traits, featuring well-being subjective symptoms. Exposure to diverse RF sources, both at home and at work, has been related to a wide spectrum of subjective symptoms. Headaches and migraines, tiredness, skin itches, and warm feelings are among the subjective symptoms reported by certain individuals and adolescents. Dizziness, blurred vision, memory loss, confusion and vagueness, toothaches, and nausea are some of the less often mentioned symptoms. These investigations are motivated predominantly by a small group of volunteers, who believed they are sensitive to EMF exposures (mobile phone or BS signal) and further perceived that they had suffered from health-related symptoms [19]–[21]. These studies have been very consistent in showing that there are no significant effects of exposure from these sources on this group's well-being.

The first research related to BS exposure was from of Zwamborn *et al.* [37]. They investigated the effects of GSM and UMTS signal exposure on cognitive functions (discussed in the preceding subsection) and self-reported well-being (reported here) on volunteers who had previously reported symptoms attributed to GSM radiation and a control group without such symptoms). Both research groups observed a slight but substantial drop in well-being after being exposed to UMTS. No effects were seen when using GSM signals either at 900 or 1800 MHz. Next, a follow-up study by Regel [19] using an improved protocol investigated the effect only of the 2140 MHz UMTS BS-like RF signal on greater numbers of volunteers, identical to that used by Zwamborn *et al.* [37]. The cognitive performance (reported in the previous subsection) and well-being were investigated for 33 self-proclaimed RF-sensitive subjects and in 84 non-sensitive subjects. Although RF-sensitive subjects generally reported more health problems, in terms of the applied field conditions, Regel *et al.* [19] observed no difference between the two groups. Subjects were similarly unable to distinguish between exposure levels, but when they suspected exposure, they reported greater health problems, suggesting that psychological aspects may be implicated in this condition.

Oftedal *et al.* [25] investigated the effect of 902 MHz mobile phone signals on 17 volunteers (five women and 12 men) who have reported to develop symptoms analogous to those reported when MPs were used in the open provocation test. During the open provocation, both the volunteers and experimenters knew when the BS was ''on'' and ''off'' and, if it was ''on'', it emitted GSM signal. Subjective symptoms were assessed in a double-blind randomized counterbalanced and crossover design for all volunteers. It was found that there was no evidence that MP exposure resulted in head pain or other health symptoms. More importantly, this study discovered that the subjects were unable to distinguish between non-exposure (Sham) and active exposure conditions, implying that a nocebo effect (negative expectation) may affect reported symptoms. Cinel *et al.* [39] used a larger number of participants in a double-blind, counterbalanced, randomized, and crossover design to prolong the patients' symptoms linked to GSM MP exposure. A total of 496 volunteers (330 women and 166 men), who had not claimed to have health symptoms due to RF exposure, were divided into three groups and exposed to Sham and actual RF signals. Although one group exhibited an induced dizziness during GSM exposure, they found no consistency in

TABLE 1. Studies on the effects of EMF exposure on the cognitive performance.

Study	Exposure Type	Design	Subject	Exclusion Criteria	No and period of exposure assessments	Exp. time (min)	Exposure Setup	SAR	E-field strength/ Power density	Crossover	Room	Measurements	Results
Koivisto et al. (2000) [32]	902 MHz; 30 min L	Single-blind, counter-balanced, pseudorandom	Healthy subjects: 24M, 24F (age range 18-34, mean age 23.2 years)	No neurological diseases	Single session	30	GSM MP mounted on the subject's head; earphone positioned on left ear with 4 cm apart from antenna	NR	-	(ON, OFF)	NR	n-back (0-3)	RT ↓ to targets (3-back Task)
Koivisto et al. (2000) [33]	902 MHz; 60 min R	Single-blind, counter-balanced, randomized	Healthy subjects: 24M, 24F (age range 18-49, mean age 26 years)	NR	2 sessions with 1 day interval	60	GSM MP mounted on the subject's head; earphone positioned on left ear with 4 cm apart from antenna	NR	-	(ON, OFF)	NR	SRT, CRT, SUB, VER, VIG, etc (12 tasks)	SRT ↓; VIG ↓SUB ↓; VIG accuracy ↑
Curcio et al. (2004) [34]	MP GSM 902.40 MHz; 45 min L (peak power of 2 W, equivalent to an average power of 0.25 W)	Double-blind, counter-balanced	Healthy subjects: 10M,10F (age range 22-31 years, mean age 26.4 ± 2.86 years)	No MP/ No neurological and psychiatric history/ No medication/ No drug intake/No sleep complaints	3 sessions with interval of ≥48 h between session	45	Helmet (antenna oriented to temporo-parietal areas and microphone oriented towards the mouth), 1.5 cm from the left ear, 2nd MP (off) on the right side of the headBSL: only helmet ON/OFF: helmet and MP	Max value: 0.5 W/kg	-	(BSL, ON, OFF)	NR	SRT, CRT, VS, SUB	SRT ↓ (POST); CRT ↓ (POST)
Regel et al. (2006) [19]	BS UMTS 2140; 45 min, 2 m	Double-blind, randomized	Healthy subjects: 33 EHS (14M 19F); 84 control (41M 43F) (age range 20-60 years, mean ± SD=37.7 ± 10.9), BMI 19–30 kg/m^2	No pacemakers, hearing aids, artificial cochlea, drugs/No smoking/No chronic diseases /No pregnancy/ No head injuries, neurologic, psychiatric/No sleep disturbances /Average alcohol, caffeinated/No shift workers/No long-haul flights (> 3 h time zone difference) within the last month	3 experimental sessions at 1-week intervals scheduled at the same time of day (~ ± 2 h)	45	The antenna at 1.5 m height and 2 m distance from the subjects, targeting the left side of the body from behind, with a field incidence angle of 25° with respect to the ear-to-ear vertical plane	-	0 V/m, 1 V/m, or 10 V/m	(0, 1, 10 V/m)	One-side -open chamber shielded with RF radiation absorbers	SRT, CRT, N-back and Visual Selective Attention	None
Curcio et al. (2008) [35]	MP GSM 902.40 MHz; 45 min R (peak power of 2 W, equivalent to an average power of 0.25 W)	Double blind, counter-balanced	Healthy subjects: 12F,12M (age range 19-36, mean age 28.17±4.78 years)	Regular sleep cycle/No coffee/ No alcohol/ No MP	Weekly interval, conducted 2 sessions between 9.00 am and 11.30 am	45	Helmet (antenna oriented to temporo-parietal areas and microphone oriented towards the mouth), 1.5 cm from the left ear, 2nd MP (off) on the right side of the head	Max value: 0.5 W/kg (absolute uncertainty within 20%)	-	(ON, OFF) x (BL, 15, 30, 45 min)	Shielded, soundproof and temperature-controlled room	SRT, sequential finger tapping	None
Cinel et al. (2008) [17]	GSM 888 MHz and CW; EXP 1: 1:45 min L/R; EXP 2: 2:40 min L/R	Double-blind, randomized, counter-balanced,	EXP 1: Healthy subjects; 116F 44M (mean age 22.2 years) EXP 2: Healthy subjects; 112F 52M (age range 18-42 years, mean age 23 ± 5 years)	No MP for at least 1 h before each session	EXP 1 and EXP 2: Weekly interval, conducted 2 sessions	EXP 1: 45 EXP 2: 40	MP was fixed on a 'cage/cap' that was mounted on the head	1.4 W/kg (±30%) (SAR average for CW and GSM) 11.2 W/kg (peak of SAR for GSM)	-	(ON, OFF)	NR	Exp 1: n-back (2-3), VIG; Exp 2: Stroop, VS, Sternberg	None
Eltiti et al. (2009) [21]	BS GSM 900 + 1800; UMTS 2020; 50 min, 5 m	Double-blind, counter-balanced, randomized	44 EHS (mean age 46.1 years, SD 13.2); 44 control (mean age 54.0 years, SD 15.4)	No brain injury /No epilepsy or claustrophobia/ No pacemaker/ No mental disease or taken psycho-active medication in 4 months prior to testing	4 sessions, weekly interval at approximately the same time of day (±3 h)	50	GSM signal (combining both 900 and 1800 MHz) and UMTS signal (2020 MHz) over the area where the participant was seated	-	10 mW/m^2	(GSM, UMTS, OFF)	Shielded room with high shielding effectiveness	DSST, DS, mental arithmetic	None
Malek et al. (2015) [22]	BS GSM 945 MHz, 1840 MHz; UMTS 2140 MHZ; 2 m	Single-blind, counter-balanced, randomized	100 EHS; 100 non-EHS	No shift worker	4 sessions	50	BS antenna (Kathrein 800 10046/GSM900/GSM 1800/UMTS) is placed at 1.5 m from the ground and 2 m distance from the subjects	-	1 V/m	(GSM 900, GSM1800, UMTS, OFF)	RF shielded room, lined using microwave absorbing sheets	Paired Associates Learning, RT, Rapid Visual Processing, Spatial Span	None

TABLE 1. *(Continued.)* **Studies on the effects of EMF exposure on the cognitive performance.**

Sauter et al. (2015) [29]	TETRA hand-held transmitter 385 MHz; 2 h 30 min L	Double-blind, balanced, randomized	Healthy subjects: 30M (age range 20–30 years, mean ±SD: 25.4±2.6 years)	No sleep disorder/ Non-smoker/ No drugs and medication/No implantations and tattoos on head	Intervals of 2 weeks, 9 daytime assessment in the afternoon at a fixed time frame	150 /day	Cushioned light weight antenna on the left side of their heads. Each exposure condition was applied at the left side of the head three times	(1) TETRA low level (max SAR 10g=1.5 W/kg) (2) TETRA high level (max SAR 10g=6 W/kg)	-	(TETRA 1.5 W/kg, TETRA 6.0 W/kg, OFF) (UMTS/LTE, OFF)	Shielded room with low background field	Test for Attentional Performance (Divided attention, VIG), Vienna Test system (Selective attention) and n-back (0-3) (Working memory)	No negative impact on cognitive functions (the cognitive functions ranged within normal limits)
Vecsei et al. (2018) [36]	MP UMTS WCDMA 1947; LTE 1750; 20 min L	Double-blind, counter-balanced, randomized	UMTS: Healthy subjects 20F 14M (aged 20 ± 3 years) LTE: 13F 13M (aged 21 ± 3 years)	No smoking/ No alcohol/ No coffee/ Moderate MP use	2 sessions with 1 week interval between session at 8 am - 6 pm	20	Patch antenna mounted in a position mimicking the normal use of an MP: the center of the patch antenna was near the exit of the ear canal, above the tragus, at a distance of 7 mm	1.8 W/kg	-	(UMTS/LTE, OFF)	Dimly lit room	Stroop test (executive function, processing speed, selective attention)	None

BSL – Baseline, CRT – Choice Reaction Time, DSST - Digit Symbol Substitution Task, DS – Digital Span, EXP – Experiment, F – Females, h – hours, L – Left, min – minutes, MP – Mobile Phone, M – Males, NR – Not Reported, POST – Post Exposure, R – Right, SD – Standard Deviation, SRT – Simple Reaction Time, SUB – Subtraction Time, VER – Verification Time, VIG – Vigilance, VS – Visual Search, ↑ - increased, ↓ - decreased.

the other two study groups. This indicates that there is no significant effect of mobile phone exposure on the well-being subjective symptoms. Sauter *et al.* [29] also suggested that there is no indication of a negative impact of a short-term EMF-effect of 385 MHz TETRA hand-held transmitter on the well-being subjective symptoms in healthy young men. Most recently, Masrakin *et al.* [40] also concluded that the continuous RF emitted from the 2.45 GHz textile antenna worn on 20 volunteers did not affect their well-being.

VI. PHYSIOLOGICAL PARAMETERS (HEART RATE, BLOOD PRESSURE AND BODY TEMPERATURE)

Few studies have validated that MP [24]–[27] and BS exposures [10], [20]–[22], [28] did not induce physiological effects (variation in blood pressure and heart rate). When both self-reported EHS and non-EHS groups were exposed to 3G Wideband Code Division Multiple Access (WCDMA) MP in [26], Kwon *et al.* discovered there is no significant physiological changes (heart rate, heart rate variability, and respiration rate). Moreover, WCDMA was found to not affect the heart rate, respiration rate, heart rate variability, or subjective symptoms in adults, according to Choi *et al.* [27]. Besides that, Malek *et al.* [22] also reported that BS transmissions had no significant short-term impacts on heart rate, blood pressure, or body temperature. Next, Andrianome *et al.* [10] observed the effects of continuous RF-EMF exposure from signals emulating GSM 900, GSM 1800, DECT and 2.45 GHz Wi-Fi signals. Similarly, it was discovered that these signals had no effect on the EHS participants' autonomic nervous system, which included blood pressure and heart rate variability. Most recently, Masrakin *et al.* [40] observed that wearing textile antennas emitting 2.45 GHz signals also had no effect on adults' blood pressure, heart rate, or body temperature. Table 2 presents the physiological parameters, EMF perception and well-being findings in the literature.

VII. EEG

Electrophysiological studies have indicated that a person's waking or resting EEG is affected by GSM MP [36], [41]–[46]. These findings consistently indicated that there were increases of alpha rhythms (∼8-12 Hz) with this exposure. Other studies show a decrease [47] and no effect [48], [49] of MP exposure on the waking EEG. Researchers in [41] investigated the effect of exposure to a GSM 900 signal on EEG waking activity and its temporal development in double-blind, cross-over design tests. The experimental procedure of this study is similar with the one reported in [34]. A total of 20 volunteers were assigned randomly to two groups, and one group was exposed for 45 minutes before the session, and the second group was exposed for 45 minutes during the session. The results demonstrated an increase of alpha power, and this finding was confirmed later when the study was replicated with a substantial sample size ($N = 120$) [41]. Further, Croft *et al.* [43] extended this study by examining three distinct age groups with mobile phone exposure operating using both GSM and UMTS technologies, involving 41 adolescents, 42 adults, and 20 elderly people in a double-blind, crossover counterbalanced design. Only the adults had increased alpha rhythms during the GSM exposure, which was consistent with the findings from [41]. However, this study failed to replicate this effect for adolescents and elderly people. Vecchio *et al.* [45] also examined the eyes-closed resting EEG in alpha rhythms, and found that they are affected by GSM radiation in inter-hemispheric functional coupling. Their results have also showed a positive correlation between the subject's age and the inter-hemispheric frontal alpha coherence. The possibility of the increase of the alpha rhythms might be due to hyper-excitability that aggravated an age-related physiological reduction of the cholinergic tone (an organic molecule that functions as a neurotransmitter in the brain). Next, Roggeveen *et al.* [46] found an increase in alpha, slow beta, fast beta, and gamma bands on adult's EEG exposed to a short-term 3G dialing mobile phone. The 3G mobile phone was dialled from a fixed line in another room during the exposure conditions. In contrast, Perentos *et al.* [47] found a reduction in alpha power on adult's waking EEG exposed to pulse-modulated GSM mobile phone, which contradicted the previous findings. The main limitation of this study was that a single-session protocol was used instead of four different

TABLE 2. Findings comparison of previous studies on the EMF perception, well-being and physiological parameters.

Study	Exposure Type	Design	Subject	Exclusion Criteria	No and period of exposure assessments	Exposure time (min)	Exposure Setup	SAR	E-field strength/ Power density	Crossover	Room	Measurements	Results
Thavanainen et al. (2004) [24]	MP; GSM 900 and 1800; 35 min	Double-blind, randomized, placebo-controlled	Healthy subjects: 16F 18 M (mean age 38.8 years, SD 10.3), mean BMI of 23.5 (SD 2.2) kg/m^2	NR	2 sessions, weekly interval at between 1 pm - 3 pm	35	Dual band MP and a physically identical but inactive MP were located on a plastic head helmet. RF field recording antenna placed around 20 cm from the active MP	900 MHz: 1.58 W/kg 1800 MHz: 0.70 W/kg	-	(GSM 900, GSM 1800, OFF)	EMF shielded laboratory	Physiological parameters (BP and HR)	No effect on BP and HR
Regel et al. (2006) [19]	BS UMTS 2140; 45 min, 2 m	Double-blind, randomized	33 EHS (14M 19F; 84 control (41M 43F) (age range 20-60 years, mean ± SD 37.7 ± 10.9), BMI 19–30 kg/ m^2	No pacemakers, hearing aids, artificial cochlea, drugs/No smoking/No chronic diseases/No pregnancy/ No head injuries, neurologic, psychiatric/ No sleep disturbances /Average alcohol, caffeinated/ No shift workers/No long-haul flights (> 3 h time zone difference) within the last month	3 experimental sessions at 1-week intervals scheduled at the same time of day (~ ± 2 h)	45	The antenna at 1.5 m height and 2 m distance from the subjects, targeting the left side of the body from behind, with a field incidence angle of 25° with respect to the ear-to-ear vertical plane	-	0 V/m, 1 V/m, or 10 V/m	(0, 1, 10 V/m)	One-side-open chamber shielded with RF radiation absorbers	5 subjective well-being symptoms	No effect on subjective symptoms
Oftedal et al. (2007) [25]	MP GSM 902.4; 30 min	Double-blind, randomized, Sham-controlled	Healthy subjects: 12M 5F (age range 20-58 years, mean=39)	No MP/No other serious health conditions/ No frequent headache/	Max takes 4 session, ≤ 2 days interval between sessions	30	Antenna mounted symmetrically at the sides of the subject's head. Wooden bars restricted the sideways movements of the head. Antenna positioned 8.5 cm from the head	Spatial peak SAR_{1g} : 1.0 W/kg SAR_{10g} : 0.8 W/kg	-	(ON, OFF)	Control room next to the shielded exposure room	4 subjective well-being symptoms Physiological parameters (BP and HR)	No effect on subjective symptoms , BP and HR
Cinel et al. (2008) [39]	GSM 888 MHz and CW; Exp 1:45 min L/R; Exp 2:40 min L/R	Double-blind, randomized, counter-balanced	EXP 1: Healthy subjects: Adults (116 M 330F, age range 18 to 42 years, mean=23, SD=4.4) EXP 2: Healthy subjects; 112F 52M (age range: 18-42, avg age 23 years, SD=5)	No MP	Weekly interval, conducted 2 sessions	40	MP attached to a cap that was then positioned on participant's head	1.4 W/kg (±30%) (SAR average for CW and GSM) 11.2 W/kg (peak of SAR for GSM)	-	(ON, OFF)	NR	5 subjective well-being symptoms	No consistent effect on subjective symptoms
Eltiti et al. (2007) [20]	BS GSM 900 + 1800; UMTS 2020; 50 min, 5 m	Double-blind, counter-balanced, randomized	44 EHS (57%M, mean age: M=46.1, SD=13.5); 114 control (57.5%M, mean age: M=54.5, SD=15.2)	No brain injury /No epilepsy or claustrophobia/ No pacemaker/ No mental disease or taken psycho -active medication in 4 months prior to testing	4 sessions, weekly interval at approximately the same time of day (±3 h)	50	GSM signal (combining both 900 and 1800 MHz) and UMTS signal (2020 MHz) over the area where the participant was seated	-	10 mW/m^2	(GSM, UMTS, OFF)	Shielded room and high shielding effective ness	6 VAS subjective well-being symptoms, 57 EHS symptoms, EMF Perception, Physiological parameters (BP and HR)	No effect on subjective symptoms, EMF perception, BP, HR
Wallace et al. (2010) [28]	BS TETRA 420; 50 min, 5 m	Double-blind, randomized, counter-balanced	48 EHS (61%F, mean ± SD = 42 ± 16; age range 18-72 years); 132 control (51%F, mean ± SD =41 ± 19; age range 18-80 years)	No brain injury, diagnosis of epilepsy, claustrophobia, diagnosis, treatment for a mental disease/ No pacemaker/ No physical impairment or illness/ No medication	3 sessions (inc open provocation session) with interval ≤ 1 week apart and same time of day	50	Participants seated 4.95 m from antenna of the BS and use TETRA signal release 1 [specification 390 392-2; European Telecommunications Standards Institute (ETSI)	271 μW/kg	10 mW/m^2	(ON, OFF)	Screened semi-anechoic chamber	6 VAS subjective well-being symptoms, 57 EHS symptoms, EMF Perception, Physiological parameters (BP and HR)	No effect on subjective symptoms, EMF perception, BP and HR (double-blind) Have effects on subjective symptoms (exposure is known)
Kwon et al. (2012) [26]	MP 3G WCDMA 1950; 64 min	Double-blind, counter-balanced, randomized	17 EHS 8M 9F (mean=3 0.1 SD=±7.6);	No caffeine/ No smoking/ No exercise Enough sleep	2 sessions with 1-10 days interval between sessions	64	Dummy MP containing a WCDMA module within a headset placed on the head	1.57 W/kg	-	(ON, OFF)	Laboratory and other electrical	8 subjective well-being symptoms Physiological parameter (HR)	No effect on subjective symptoms and HR for

TABLE 2. *(Continued.)* **Findings comparison of previous studies on the EMF perception, well-being and physiological parameters.**

			20 control 11M 9F (mean=29.4 SD=±5.2)								devices were unplugged except for instruments		EHS,non-EHS subjects
Choi et al. (2014) [27]	MP 3G WCDMA 1950; 64 min	Double-blind, randomized	26 adults 13M 13F (mean=28.4 SD=±5.1); 26 teenagers 13M 13F (mean=15.3 SD=±0.7)	No caffeine/ No smoker/ No exercise before day experiment	2 sessions with 1-10 days interval between sessions	64	Dummy MP containing a WCDMA module within a headset placed on the head	1.57 W/kg	6.9 V/m	(ON, OFF)	Laboratory and other electrical devices were unplugged except for instruments	8 subjective well-being symptoms Physiological parameter (HR)	No effect on subjective symptoms and HR
Malek et al. (2015) [22]	BS GSM 945 MHz, 1840 MHz; UMTS 2140 MHZ; 2 m	Single-blind, counter-balanced, randomized	100 EHS; 100 non-EHS	No shift worker	4 sessions	50	BS antenna (Kathrein 800 10046/GSM900/ GSM1800/UMTS) is placed at 1.5 m from the ground floor and at 2 m from the subjects	-	1 V/m	(GSM 900, GSM1800, UMTS, OFF)	RF shielded room, lined using microwave absorbing sheets	Physiological parameters (BT, BP and HR)	No effect on physiological parameters (BT, BP and HR)
Andriaome et al. (2017) [10]	BS GSM 900, GSM 1800, DECT and Wi-Fi 2.45 GHz; 5 min (for each signal)	Double-blind, counter-balanced	10 EHS (8F 2M age range 35-63 years, mean age: 48 ± 10); 25 non-EHS, mean age: 46 ± 10	No alcohol/ No coffee for the 24 hours prior to and during the study; None EHS participants were on medication	2 session intervals of ≤ 1 week	5	No external EMF sources were allowed and the exposure consisted of a series of EMF signals emitted from a generator and a horn antenna	-	1 V/m	(GSM 900, GSM 1800, DECT, Wi-Fi, OFF)	Shielded chamber	Autonomic nervous system that includes BP and HR	No effect on physiological BP and HRV
van Moorselaar et al. (2017) [38]	BS GSM 900, GSM 1800, UMTS, DECT and Wi-Fi 2.45 GHz; 150 min	Double-blind, randomized, controlled	42 EHS (32F 10M, mean age 55 years, range 29–78)	Inability to complete the administered questionnaires, communicate with the study assistant/ self-reported symptoms exceeded 15 min	Testing group then follow up at 2 months interval	150	2 custom-made mobile exposure units. Different types of non-ionizing EMF can be generated a) radiofrequency EMF ("RF-unit"): GSM 900, GSM 1800, cordless MP ("DECT phone", 1880–1900 MHz), UMTS and Wi-Fi; and b) extremely low-frequency magnetic fields ("ELF-unit")	-	Max: 6 V/m (average exposure levels at the upper body level)	(GSM 900, GSM 1800, UMTS, DECT, Wi-Fi)	Home and another location where they felt comfortable	EMF Perception, symptoms	No effect on EMF perception but have effects on EHS symptoms
Boger et al. (2018) [23]	BS GSM 900, GSM 1800, UMTS, DECT and Wi-Fi 2.45 GHz; 6 h	NR	7 EHS (4F 3M)	No applicants with knowledge on their personal EMF exposure/ No depression, anxiety disorder, burnout, psychosis, chronic fatigue syndrome, fibromyalgia	4 sessions with intervals of 6 h prior to filling out the diaries in the morning, afternoon and evening	360	EME-SPY 121 exposimeters (Satimo, Cortaboeuf, France) worn at the hip in a camera bag	-	2.5 V/m	(GSM 900, GSM 1800, UMTS, DECT, Wi-Fi)	At home inside, at home outside, at work or educational institution, elsewhere, travelling	EMF Perception, EHS subjective symptoms	Have effects on EHS symptoms
Masrakin et al. (2019) [40]	Wearable textile antenna 2.45 GHz; 50 min	Single-blind, counter-balanced, randomized	Healthy subjects 10M 10F (age range= 23-31 years, avg age 25 years and SD = 2.4, BMI 19-26 kg/m²)	No artificial cochlea, hearing aids, pacemakers/ No smoking/No alcohol/ No caffeinated drinks/ No psychiatric disease/ No drug in the previous 6 months/ No long-haul flight for >3 h of different time zones/No shift workers/ Matched menstrual cycle	2 sessions	50	Mounted Tx onto the upper right arm. Both the Tx and Rx antennas were both vertically oriented (with the radiator placed on the top section) when mounted on the subject's body. Rx was mounted on the left chest of the subjects	For 10g SAR TM: (2.88 W/kg); 10g SAR TP: 0.35 W/kg)	-	(ON, OFF)	RF-shielded room	10 subjective well-being symptoms, Physiological parameters (BT, BP and HR)	No effect on subjective symptoms and physiological parameters (BT, BP and HR)

BMI – Body Mass Index, BP – Blood Pressure, BT – Body Temperature, CW – Continuous Wave, EHS– Electromagnetic Hypersensitivity, ELF – Electromagnetic Low Frequency, F – Females, H – Hours, HR – Heart Rate, HRV – Heart Rate Variability, M – Males, Min – Minutes, NR – Not Reported, Rx – Received Antenna, SD – Standard Deviation, TM – Textile Monopole Antenna, TP – Textile Patch Antenna, Tx – Transmitted Antenna, VAS – Visual Analogue Scale.

TABLE 3. Studies on the effects of EMF exposure on the resting EEG recorded with the eyes open or closed.

Study	Exposure Type	Design	Subject	Exclusion Criteria	No and period of exposure assessments	Exposure time (min)	Exposure Setup	SAR	E-field strength/ Power density	Crossover	Room	Measurements	Results
Huber et al. (2002) [44]	Pulse-modulated GSM 900; 30 min; L	Double-blind, balanced	Healthy subjects: 16M (age range 20–25 years; mean age in (PET) study 22.5 years, in sleep study 22.3 years)	No caffeine/No alcohol/ No medication/ Maintain regular sleep–wake schedule/ No MP /No subjects with sleep apnea, nocturnal myoclonus and low sleep efficiency	2 sessions ≤ 1-week intervals between exposures	30	Subjects sat on a chair with their heads positioned between two plates to ensure a well-defined location with respect to two planar antennas	Spatial peak (SAR) averaged over 10 g = 1 W/kg	-	(ON, OFF)	Sleep laboratory	10 min eyes closed	9-11 Hz↑ (During)
Curcio et al (2005) [41]	GSM 902.40; 45 min L	Double-blind	Healthy, subjects: 10M 10F (mean age 26.4 ± 2.86 years, range 22–31)	No neurological, psychiatric history / No medication/ No drug	3 sessions	45	Helmet to hold the MP in the usual position of use (the antenna oriented to the temporo-parietal areas whereas the microphone is directed towards the mouth) 1.5 cm from the left ear.	0.5 W/kg	-	(BSL, ON, OFF)	NR	7 min eyes closed	9-10 Hz↑; 11 Hz↑ (During)
Croft et al. (2008) [42]	GSM 895; 30 min L/R	Double-blind, counter-balanced, randomized	Healthy subjects: 46M 74F (mean age 31 ± 13 years, age range 18-69)	No psychological, neurological condition, serious head injury/ No extended period of unconsciousness. Normal hearing, and normal (or corrected-to-normal) vision	2 sessions with 1 week interval	30	A GSM MP set via laptop and manufacturer software to continuously transmit a 895 MHz digital signal	Without EEG apparatus: 0.674 W/kg Max MP's antenna (apparatus over the ''temporal lobe''): 0.110 W/kg	-	(ON, OFF) x (DURING, POST)	NR	10 min eyes open (during); 10 min eyes open (post)	8-12 Hz↑ (During)
Croft et al. (2010) [43]	GSM 895; 50 min UMTS 1900 MHz; 50 min L/R	Double-blind, counter-balanced, randomized	21M 20F adolescents (age range 13–15 year, mean=14.1, SD=0.87) ; 21M 21F young adults (age range 19–40, mean=24.5, SD=4.51) ; 10M 10F elderly (range age 55–70, mean=62.2, SD=3.94)	No smokers/ No hearing problems/ No psychiatric medication/ No history of psychiatric disorders/ No history head injury/ No caffeinated beverages and alcohol for 24 h prior to testing	3 sessions on separate ≤4 days interval	50	Cradle containing a 2G handset was placed on one side of the head and a 3G handset on the other side, with neither MPs transmitting	2G (900MHz) : SAR= 0.7 W/kg, max peak spatial (10g) = 0.7W/kg 3G (1900MHz): max peak spatial: 1.7 W/kg		(GSM, UMTS, OFF) x (PRE, DURING, POST)	Sound attenuated and metal-shielded recording room	10 min eyes open (during); 5 min eyes open (after cognitive test 1); 5 min eyes open (after cognitive test2); 5 min eyes open (post)	8-12 Hz↑ (During GSM for adults only) None (UMTS for any groups)
Vecchio et al. (2010) [45]	GSM 902.40; 45 min L	Double-blind	Elderly (11F 5M, age range 47-84 years) 15 young adults M (age range 20-37)	No caffeinated/ No alcohol/ regular sleep habits/No MP/ Postmenopausal	2 sessions with weekly interval	45	Helmet holding two MPs. MPs were oriented in the normal position. In one session the signal was turned on for 45 min (GSM), in the other one it was turned off.	Max: 0.5 W/kg	-	(ON, OFF) x (PRE, DURING, POST)	NR	5 min eyes closed (before); 5 min eyes closed (during)	8-12 Hz↑ (Inter-hemispheric coherence) (During)
Perentos et al. (2013) [47]	GSM 900; 20 min R	Double-blind, counter-balanced, randomized	Young adults 35F 37M (mean age 24.5 years, SD= 5.4 years)	No alcohol/ No MP/ No caffeine consumption within the 6 h prior to the experiment	4 sessions	20	MP placed according to the standard ear-to-mouth position, over the right hemisphere. The speaker and antenna located over the auditory canal. MP in place with a specially constructed cradle	10-g peak spatial-average SAR level of 1.95 W/kg	-	(CW RF, PULSED RF, ELF, OFF) x (PRE, DURING, POST)	Electro magnetically metal-shielded room	5 min eyes open (before); 20 min eyes open (during); 5 min eyes open (post)	8-12 Hz↓ (Pulse RF) (During)
Trunk et al. (2013) [48]	3G UMTS 1947 MHz; 30 min	Double-blind	Healthy subjects: 8M 9F (mean age 21.7 years ±3.47);14M 12F (mean age 24.08 years ±6.68)	NR	2 sessions with weekly interval	30	Patch antenna placed next to the right ear	1 g: 1.75 W/kg		(ON, OFF) x (PRE,POST)	Dimly lit room	10 min eyes open (before); 30 min eyes open (during); 10 min eyes open (post)	None
Loughran et al.	GSM 900; 30 min L	Double-blind, counter-	Healthy subjects 12M 10F	No caffeine/ Regular	3 sessions at weekly intervals and	30	Two planar antennas (left active only) on the participants head	'High SAR': 1.4 W/kg	-	(HIGH SAR, LOW SAR, OFF)	NR	3 min eyes open and 3 min eyes closed (before); 3	None

TABLE 3. ***(Continued.)*** **Studies on the effects of EMF exposure on the resting EEG recorded with the eyes open or closed.**

(2013) [49]		balanced, randomized,	adolescents (age range 11-13, mean=12.3±0.8 years) 31F	bedtimes starting three days before each study day/ No physical exercises /No MP	performed at the same time of day			'Low SAR' (psSAR): 0.35 W/kg		x (PRE, POST)		min eyes open and 3 min eyes closed at 0 min, 30 min and 60 min (post)	
Roggeveen et al. (2015) [46]	UMTS 1929.1 to 1939.7 MHz; 15 min L ear and heart	Single-blind, counter-balanced	young adults (mean age=26.7 years; SD = 8.5)	No smoker/ No medical history of cardiac, nervous system disorders/ No caffeine-containing beverages/ No alcohol/ Sufficient night rest	2 sessions with a maximum of 2 days in between the two sessions	15	MP/sham- MP placed directly onto the left ear at approx. 45°. In the other session, the MP was placed adjacent to the left side of the sternum, bordering the sternoclavicular joint	0.69 W/kg	-	(ON, OFF) x (PRE, DURING, POST)	Electrically non-shielded, room	15 min eyes closed (before);15 min eyes closed (during) and 15 min eyes closed (post)	α↑, β_{slow} ↑, β_{fast} ↑, and γ↑ (During)
Vecsei et al. (2018) [36]	MP UMTS WCDMA 1947; LTE 1750; 20 min L	Double-blind, counter-balanced, randomized	UMTS: Healthy subjects 20F 14M (aged 20 ± 3 years) LTE: 13F 13 M (aged 21 ± 3 years)	No smoking/No alcohol/No caffeine/ Moderate MP use	2 sessions with 1 week interval between session at 8 am - 6 pm	20	MP was connected to an RF amplifier via the external antenna output of the MP. The patch antenna was connected to the output of the RF amplifier. The patch antenna was mounted in a position mimicking the normal use of an MP: the center of the patch antenna was near the exit of the ear canal, above the tragus, at 7 mm	1.8 W/kg	-	(UMTS/LTE, OFF)	Dimly lit room	5 min eyes closed (before);20 min eyes closed (during) and 5 min eyes closed (post)	8-12 Hz↓ (During)

BSL – Baseline, CW – Continuous Wave, DURING – During exposure, EEG – Electroencephalography, ELF – Electromagnetic Low Frequency, F – Females, L – Left, h – hours, M – Males, min – minutes, MP – Mobile Phone, NR – Not Reported, PRE – Pre-exposure, POST – Post exposure, R – Right, SD – Standard Deviation, α – Alpha wave, β – Beta wave, γ - Gamma wave, ↑ - increased, ↓ - decreased.

sessions, one for each type of RF exposure. Thus, its accuracy may be affected due to the carry-over effects of the exposures. On the other hand, several other recent evidence proved that there is no effect of UMTS [48] and GSM [49] mobile phone exposure on the waking EEG. Trunk *et al.* [48] investigated the possible effects of mobile phone radiating using a commercial patch antenna operating in different frequency bands on the spectral power of the human resting EEG. A modest number of subjects ($N = 17$) were involved in this study, which used double-blind, counterbalance, and crossover design. The subjects were exposed to Sham and UMTS signals by positioning the patch antenna on the subject's right ear, mimicking the use of a mobile phone for under 30 minutes The exposure to the UMTS EMF did not induce EEG spectral power in the resting condition, and is in agreement with the results from [43].

In a more recent study, Vecsei *et al.* [36] found a decrease in alpha band on adult's EEG exposed to a short-term 3G and 4G mobile phone. The findings suggest that the brain networks that underpin global oscillations may need minimal remodeling to respond to the local biophysical alterations resulting from RF-EMF mobile phone exposure. All aforementioned state-of-the-art studies thus far (summarized in Table 3) have focused on investigating the effect of RF-EMF exposure from MP on EEG, and none of these studies have investigated the effects from BS exposure.

VIII. DISCUSSION

A substantial number of studies investigated the effects of radiation from MPs and BSs on the cognitive performance through behavioral measures such as RT and attention in a wide range of tasks. More than half of the studies shown

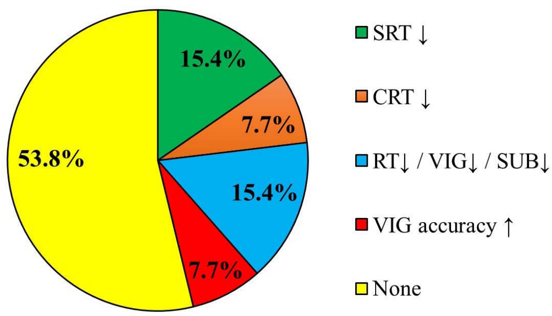

FIGURE 2. Overview of the ten selected studies which investigated the effects of EMF exposure on the cognitive performance. CRT – Choice Reaction Times, RT – Reaction Times, SRT – Simple Reaction Times, SUB – Subtraction, and VIG – Vigilance.

in Figure 2 found that there is no indication of any negative impact of a short-term EMF-effect on cognitive function [17], [19], [21], [22], [29], [35], [36]. SRT, RT, VIG and SUB were decreased when the RF-EMF was off (RF-off) to on (RF-on), indicated by 15.4% from the findings in [32]–[34]. Meanwhile, the study with the least percentage (about 8%) in Figure 2 showed that the exposure by MPs on adults resulted in a reduction in CRT [34]. On the contrary, a rise in accuracy of VIG is reported in [33].

To further examine whether EMF exposure affects human behavior, studies and findings on the well-being subjective symptoms and physiological parameters are summarized in Figure 3. The effect of RF-EMF on the physiological parameters from the previous studies showed that the exposure of RF signal does not affect the volunteers' heart rate (50%), blood pressure (39%) and body temperature (11%) [10], [20], [22], [24]–[28], [40]. Similarly, a majority (70%) of these studies

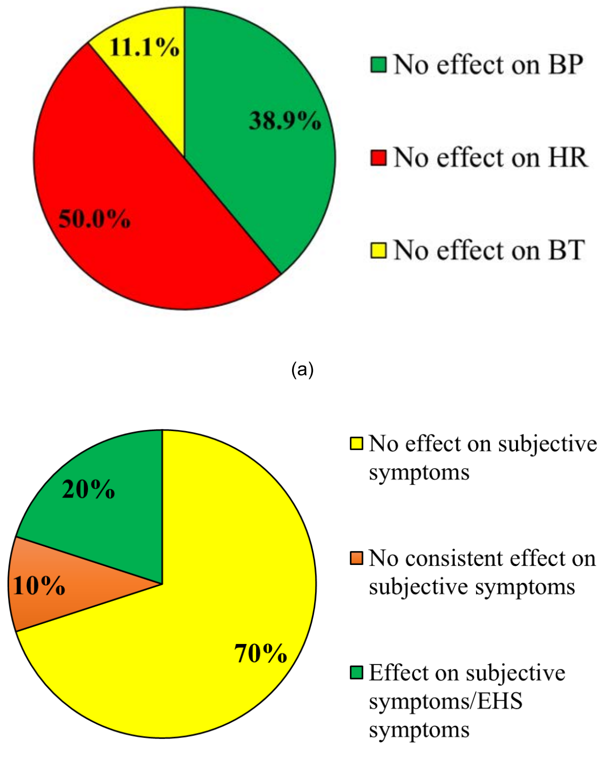

FIGURE 3. Overview of the 13 selected studies which investigated the effects of EMF exposure with respect to physiological parameters (a) BP - Blood Pressure, BT – Body Temperature, EHS – Electromagnetic Hypersensitivity, and HR – Heart Rate and (b) well-being.

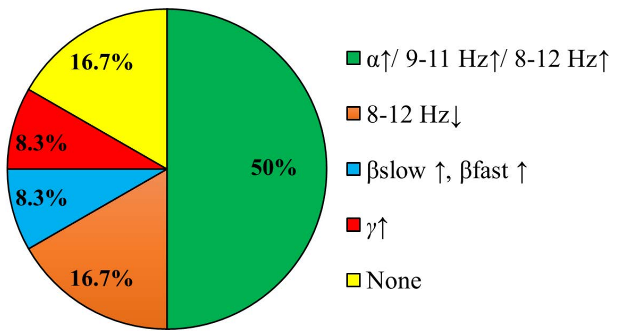

FIGURE 4. Overview of the ten selected studies which investigated on the effects of EMF exposure on the resting EEG recorded with the eyes open or closed. α – Alpha wave, β – Beta wave, and γ - Gamma wave.

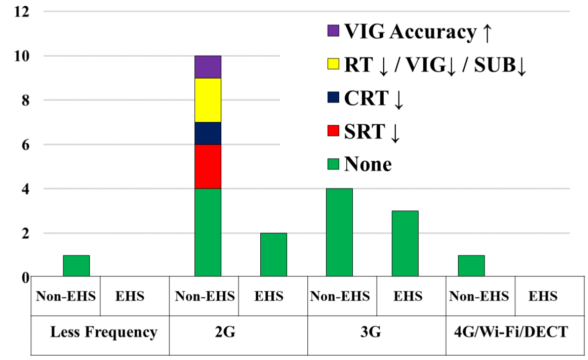

FIGURE 5. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi-Fi/DECT on the cognitive performance and their measurement results. CRT – Choice Reaction Times, EHS – Electromagnetic Hypersensitivity, RT – Reaction Times, SRT – Simple Reaction Times, SUB – Subtraction, and VIG – Vigilance.

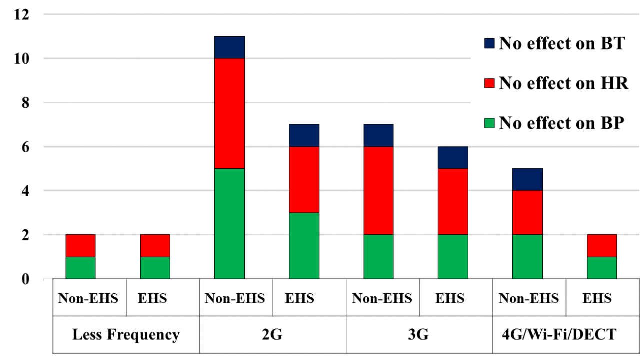

FIGURE 6. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi-Fi/DECT on the physiological parameter (body temperature, heart rate and blood pressure) and their measurement results. BP – Blood Pressure, BT – Body Temperature, EHS – Electromagnetic hypersensitivity, and HR – Heart rate.

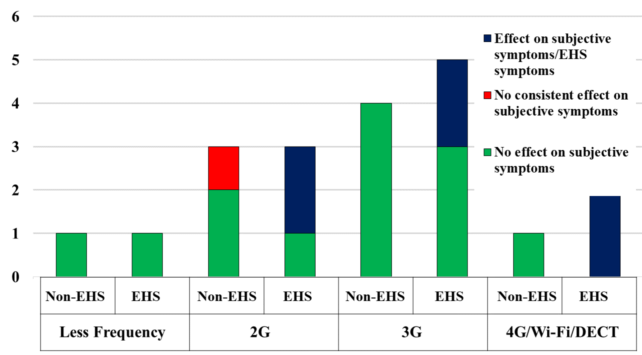

FIGURE 7. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi-Fi/DECT on the well-being subjective symptoms studies and their measurement results. EHS – Electromagnetic Hypersensitivity.

on well-being parameters reported that mobile phone and BS exposures did not induce subjective symptoms [19], [20], [25]–[28], [40]. However, minority of these studies (20%) found significant changes on subjective symptoms [23], [38] and indicated no consistent effects [39] when exposed to RF-EMF signal (10%).

Electrophysiological studies have revealed that a person's waking or resting EEG is affected by exposure to RF signals from GSM mobile phone [41]–[47]. Based on Figure 4, the most significant observation is the increase in alpha rhythms (∼8-12 Hz/9-11 Hz) [41]–[46] due to mobile phone exposure (50%). The increase of the alpha rhythms is interpreted as an altered cortical neuronal activity, probably mediated by changes in thalamic functioning [41], [44]. The smallest percentage (8.3%) from the overall studies indicated only effects of slow beta, fast beta, and gamma bands on adults' EEG when exposed to a short-term 3G dialing mobile phone [46].

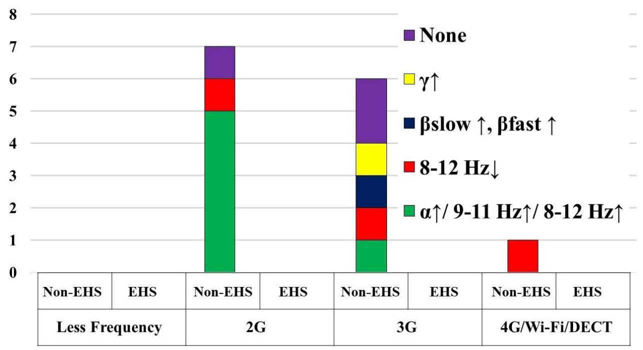

FIGURE 8. Bar chart for studies on the exposure of 2G, 3G and 4G/Wi Fi/DECT on EEG studies and their measurement results. EHS – Electromagnetic Hypersensitivity, α – Alpha wave, β – Beta wave, and γ – Gamma wave.

On the contrary, some authors found a reduction in alpha power on adult's waking EEG exposed to pulse-modulated GSM [47], 3G and 4G [36] mobile phones.

The effects of RF-EMF radiation from mobile phones, BSs, and Wi-Fi on the human cognitive function, well-being health symptoms, physiological parameters (blood pressure, heart rate, and body temperature), and EEG is tabulated in Table 1, Table 2, Table 3. Their results are illustrated in Figure 2, 3, and 4, indicating inconsistency. Results of the exposure to the GSM900/GSM1800/UMTS/4G MPs, GSM900/GSM1800/UMTS BS, DECT and Wi-Fi are shown in in Figures 5, 6, 7 and 8. These research studies involved both EHS or non-EHS subjects evaluated in terms of cognitive performance, well-being, physiological and EEG parameters.

Based on Figure 5, most of the RF signals which affected the cognitive performance is 2G, followed by 3G signals. Most of these studies indicated that the signal transmitted has no effect on the subject's intellectual performance. Researchers in [29] evaluated a TETRA hand-held transmitter with the longest duration of 2 hours and 30 minutes in the shielded room, whereas [36] performed the same investigation with at least 20 minutes of exposure. Both investigations validated that there are no changes/negative effects on their subjects' cognitive ability. The results in [29] showed one effect on working memory (faster RT in 2-back task) that reflected an improvement in performance of cognitive function. However, results from [32]–[34] validated that there are changes in their cognitive performance, with decreased RT, SRT, CRT, SUB, VIG and increased VIG accuracy. The locations of these experiments are not mentioned, and this may potentially be a factor which influenced the findings. Figure 6 shows that most studies on physiological parameters, specifically for vital signs such as body temperature, heart rate, and blood pressure, showed no differences from previous studies. The number of studies conducted on EHS subjects is comparable to the number of studies conducted on non-EHS group. RF signal involving a lower frequency band (420 MHz) is presented only by [28] using TETRA

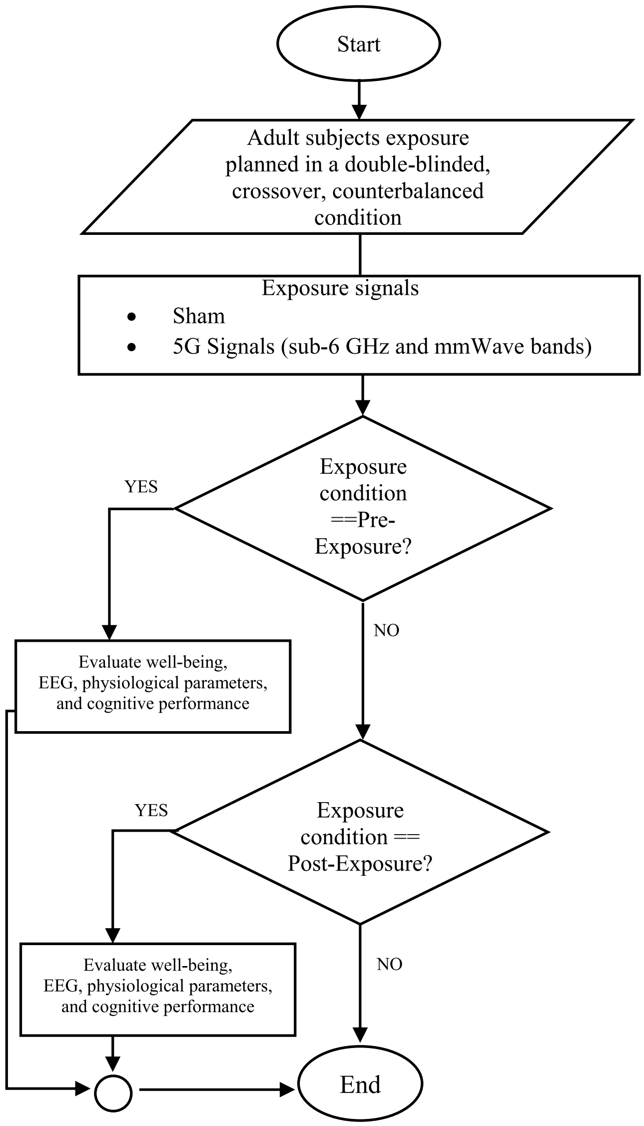

FIGURE 9. Proposed flowchart to study the effects of 5G BS exposure signals for sub-6 GHz and mmWave bands (up to 30 GHz) on human subjects.

BS, as depicted in Figure 7. It is evident from Figure 7 that majority of these research indicated that there is no impact on subjective symptoms. Most studies on the EEG pointed that α waves of the brainwaves increased, as shown in Figure 8.

In general, this analysis indicated that all previous research aimed to determine the effects of TETRA/2G/3G/4G/Wi-Fi/DECT on health-related parameters. None of them investigated the effects of the human exposure to 5G signals, both in the sub-6 GHz and millimeter wave bands (of up to 30 GHz). Thus, further research into the effects of 5G on human health is clearly required, as most available studies on the cognitive performance, physiological parameters, and well-being of human are limited to the use of GSM900/GSM1800/UMTS/4G mobile phone, GSM900/GSM1800/UMTS base station, DECT and Wi-Fi signals. Moreover, the effects of 5G base station signals (centered at 700 MHz, 3.5 GHz, or 28 GHz) have

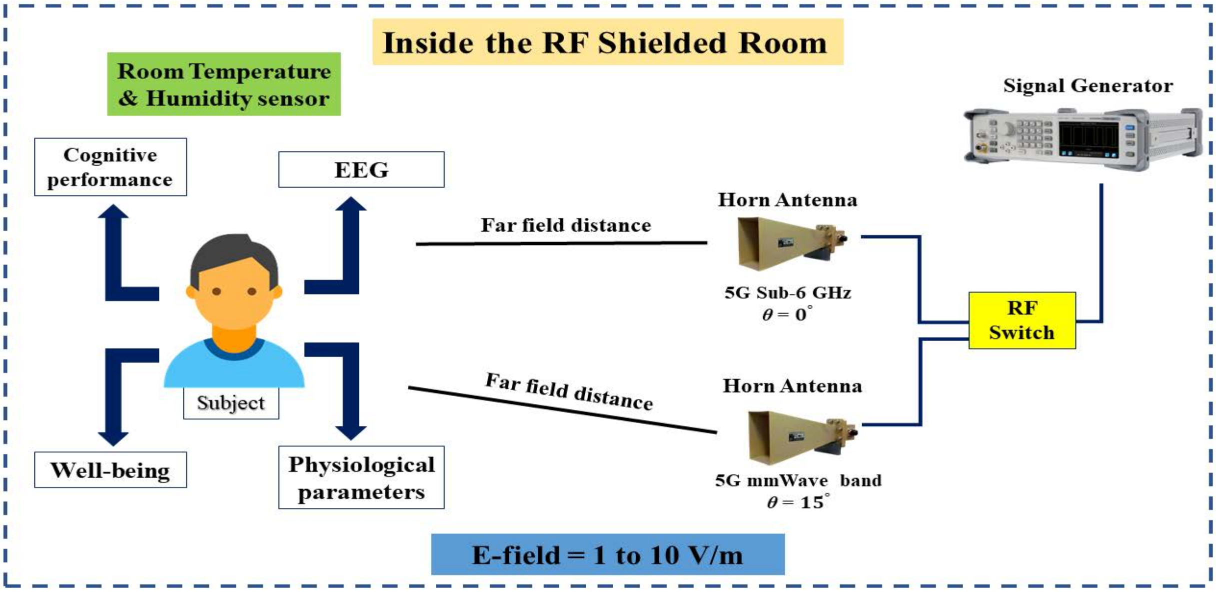

FIGURE 10. Proposed schematic diagram to study the effects of 5G BS exposure signals for sub-6 GHz and mmWave bands (up to 30 GHz) on human subjects. θ – angle of horn antenna's positioning towards subject.

not considered. Most importantly, based on this exhaustive literature review, there are yet any published evaluations studying the effects of exposure from 5G base stations on the cognitive performance, well-being, and physiological parameters (heart rate, blood pressure, body temperature) in adults. Secondly, more than half of the studies in literature focused on the RF-EMF effects due to exposure from MPs, reporting a maximum average SAR of 1.95 kg/W [47]. This value does not exceed the current ICNIRP exposure guideline for the public, which is 2 W/kg near the human head. Meanwhile, the power densities used in all studies were limited to a maximum of 10 V/m. This value is also well below the ICNIRP limit for the public. Available studies also showed that higher SARs and E-field strengths did not induce any health effects (well-being, cognitive performance) and physiological parameters, neither when exposed to RF-EMF from MPs and BSs. However, when exposed to MPs (for 2G, 3G and 4G signals) with higher SAR values, EEG decrease is observed in [36], [47]. Despite that, there is again yet any study reporting the effects of BS signal exposure on the EEG of human.

Note that there exist several significant differences in terms of methodology and the protocols previous studies when examining the effects of RF-EMF exposure on the cognitive functions. The first key parameter is the dosimetry configuration. There are two types of exposure reviewed here: (i) MP/TETRA hand-held/wearable textile antenna and (ii) BS. Therefore, different dosimetry methods are needed according to the types of radiating devices. Power density and SAR are the two most widely accepted metrics to measure the intensity and effects of RF-EMF exposure [18]. For MP/TETRA hand-held and wearable antenna exposures, the dosimetry standard used is SAR due to the close proximity between such radiating structures and the human head/body, and is within the near-field region. Meanwhile, power density or E-field strength dosimetry is used to assess BS exposure, as they are in the users' far-field region. SAR is defined as a measure of the power absorbed per unit of mass (human body tissue). It can be spatially averaged over the total mass of an exposed body or its parts, and is calculated from the root-mean-square electric field strength, E defined in volts per meter (V/m), calculated as follows [40]:

$$SAR = \frac{\sigma \cdot E}{\rho} = c\frac{\partial T}{\partial t}\bigg|_{t\to 0^+} \tag{1}$$

The conductivity, σ is defined in Siemens per meter; and the mass density, ρ represents the biological tissue density in kilogram per cubic meter. SAR also describes the initial rate of temperature rise of a tissue, $\partial T/\partial t$ as a function of the specific heat capacity (c). The power density, S is related to the electric field strength E by the free space impedance $Z_0 = 120\pi\,[\Omega]$ according to the following expression [1]:

$$S = \frac{E^2}{Z_0} = \frac{E^2}{120\pi} \tag{2}$$

The studies in [32], [33] which found changes in the cognitive function of human upon exposure, however, did not report the SAR levels. On the other hand, other studies which reported SAR levels [17], [29], [35], [36] and E-field strength/power density [19], [21], [22] indicated that the exposures did not affect or show negative effects on the cognitive functions of the volunteers, as shown in Table 1. Note also that all studies reported SAR levels within the regulatory limits of either 2 W/kg for the human head, 4 W/kg for the human limb, or E-field strength/power density within the limit of 61 V/m or 10 W/m^2 between 2 and 300 GHz, as specified by ICNIRP.

Another key observation is that assessments of cognitive functions were performed in either unknown or varying room conditions. For instance, the experimental room conditions are not reported in [32]–[34]; whereas these studies reported variations in cognitive performance due to MP exposure. However, Curcio *et al.* [35] replicated the work in [34] by conducting the experiment in a shielded, soundproof, and temperature-controlled room to assess cognitive functions of volunteers. As a result, they observed that the MP exposure did not affect any cognitive functions. Similarly, other studies in [19], [21], [22], [29], [36] reported the room conditions but observed no effect or negative effect of MP and BS exposures on cognitive function. Conversely, the only study which reported no effect of MP exposure on the cognitive function did not clarify the room condition [17]. In short, the studies observing effects on the cognitive performance of volunteers have either not reported their SAR/ E-field strength/power density levels or the room conditions. The possible remedy to this is to characterize the impacts on cognitive performance solely due to the BS RF-EMF exposure in 5G sub-6 GHz or mmWave range in terms of E-field/power density dosimetry. Such exposure experiments also need to be performed in an RF-shielded room to minimize the interference from other EMF sources and the effects of variable room temperature and relative humidity, as these factors may considerably affect the outcomes [26]. In general, the presented studies mainly showed no indication of RF-EMF effects on the well-being subjective symptoms and physiological parameters. On the contrary, the significance of this exposure is rather unclear when the EEG was investigated, as there are contradictory findings. RF-EMF exposure is seen to affect EEG even when the experiments were performed in a controlled environment (inside the RF-shielded room).

IX. CONCLUSION

This work presents an analysis of exposure studies conducted using signals from 400 MHz to 1750 MHz (for 4G). From this analysis, the following conclusions are made:

- Most of the studies in literature using 2G/3G/4G showed no effects and no consistency in how exposure to these signals affected the cognitive, physiological parameters, well-being, and EEG of the volunteers.
- Most research on human cognition, physiological parameters, and well-being so far have focused on the impacts of GSM900/GSM1800/UMTS/4G MPs, GSM900/GSM1800/UMTS BSs, DECT, and Wi-Fi exposures.
- There is an absence of studies reporting the effects of 5G (700 MHz, 3.5 GHz, or 28 GHz) BS signals on adults in terms of cognitive performance, well-being, or physiological markers (heart rate, blood pressure, and body temperature).

Figure 9 and 10 illustrated the possible flowchart and schematic diagram to study the effects of 5G BS exposure signals for sub-6 GHz and mmWave bands (of up to 30 GHz) to human subjects. Data from such a study will be useful in explicitly determining the significance signal exposure from 5G BS on human health, considering their much closer proximity to users.

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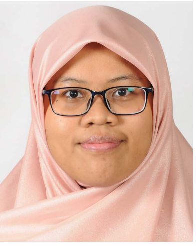

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