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IMPLICATIONS OF 5G NETWORKS FOR MENTAL PERFORMANCE: WHAT CONTROLLED HUMAN STUDIES SHOW AND WHY SAFETY PRECAUTIONS STILL MATTER

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Abstract The introduction of the fifth generation of wireless communication (5G) is a major evolution in the relationship between humans and the technological environment, with a greater density of infrastructures and a continuous exposure to electromagnetic fields (EMF). This paper focuses on the impact of 5G networks on mental performance and work ability from the ergonomics and safety perspective. A review of controlled human studies and especially the ones using electroencephalography (EEG) has concluded that there is no statistically significant modification of the spontaneous electrical activity of the human brain during acute exposure to 5G signals at a frequency of 3.5 GHz, in healthy subjects. These results suggest simply that exposure at internationally prescribed limits does not produce impairment of basic cognitive functions that are relevant to work ability. However, from an ergonomic point of view, great gaps have been found in the knowledge of the effects of millimeter waves (frequency ranges above 24 GHz) on the neurological system and mental health in the long term. Although current ICNIRP safety standards are effective in protecting against proven thermal effects, the current majority view in the scientific community highlights the importance of implementation of the "precautionary principle" because of possible cumulative biological responses that may impact cognitive integrity and long-term safety of users. The paper concludes that in order to ensure safe human interaction with 5G technology, additional interdisciplinary research into high frequencies and transparent public communication about scientifically grounded risks is required.

Keywords: 5G; mental performance; safety; health; ergonomics; RF-EMF; controlled human exposure; cognitive performance; EEG; millimeter waves; SAR; power density; ICNIRP.

1. INTRODUCTION

The introduction of 5G technology is a major evolution in wireless communications and promises extremely high data transfer speeds and minimal latency, through the use of a wide frequency spectrum, including millimeter waves. While the view from communication engineering is that perceived health risks are often not backed by scientific evidence and that existing regulatory frameworks are sufficient to protect people, the scientific community is cautious because of the specific features of 5G networks, such as the densification of the antennas and the continuous exposure of the population.

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Mobile phone use is widespread worldwide, with an estimated 6.9 billion subscriptions globally [1]. Given the size of the mobile phone user population, international public health guidance makes the point that any potential public health impact should be investigated, understood and monitored. In human volunteer research, investigators have conducted studies on the RF-field effects on end points that involve the electrical activity of the brain and cognitive functions. Tissue heating is referred to as the main interaction mechanism between radiofrequency energy and the human body [1]. A main interpretive framework for RF bioeffects is that thermal mechanisms are central and some of the reported "nonthermal" effects may actually be thermal in nature, while subtle thermal effects may occur without having consequences for health or safety [2].

Because RF EMFs allow technologies such as mobile telecommunications, Wi-Fi, and Bluetooth, ICNIRP (International Commission on Non-Ionizing Radiation Protection) has revised guidelines designed to protect humans from exposures in the frequency range of 100 kHz to 300 GHz [3]. According to ICNIRP, the primary purpose of its RF guidelines is to ensure a high level of protection against the adverse health consequences in the scientifically substantiated exposure scenarios. Even though the guidelines are based on the best available science, ICNIRP explicitly acknowledges knowledge limitations and says the guidelines will be periodically revised as the science progresses.

In the 5G era, mobile systems are extended to the millimeter-wave range, including bands roughly between 24.25 and 52.6 GHz [4]. Due to spectrum shortage in conventional cellular bands, mmWave frequencies (30-300 GHz) have attracted strong interest for next-generation cellular networks, supported by the availability of far greater spectrum and the use of high-dimensional antenna arrays [5]. However, for frequencies above 6 GHz, RF energy absorption is mainly limited to superficial tissues, which is one of the important considerations for 5G millimeter-wave exposure assessment [3]. Millimeter-wave exposures are said to be absorbed mainly in superficial tissues such as the skin and cornea [6].

In the context of RF dosimetry, the specific absorption rate (SAR) in W/kg quantifies electromagnetic power dissipated per unit mass is used [7]. In a controlled protocol used to study human EEG, 3.5 GHz exposure within the limits of current safety regulations in one study did not affect brain activity in healthy young adults [7]. In a randomized double-blind study with UMTS/LTE exposure, no effects were found on performance on the Stroop test, although EEG changes were measurable [8]. In line with this, the recent evidence review of ICNIRP concludes that there is not sufficient plausible evidence of harm from RF exposure below currently established thresholds [9].

The International Agency for Research on Cancer (IARC) has classified radiofrequency electromagnetic fields as possibly carcinogenic to humans (Group 2B) [10 World Health Organization, n.d.]. At the frequencies of mobile phones, the majority of the RF energy is absorbed in the superficial tissues, and there is negligible temperature increase in the brain and/or other organs. To date, research does not suggest consistent evidence of adverse health effects from RF exposure at levels below those that cause tissue heating [10].

2. PHYSICAL CHARACTERISTICS OF 5G EXPOSURE

5G New Radio (NR) is specified to operate in different frequency bands, which include FR1 (410 MHz-7125 MHz) and FR2, where FR2 consists of FR2-1 (24250 MHz-52600 MHz) and FR2-2 (52600 MHz-71000 MHz) [11]. ICNIRP further states that at these higher frequencies, power absorption occurs mainly in the tissues of the skin surface, where localised temperature increase is

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more significant than the core temperature increase [3]. For local exposure above 6 GHz, ICNIRP indicates that local S_{ab} is averaged over a square 4 cm^2 body surface area, and that exposure averaged over 1 cm^2 is limited to two times the 4 cm^2 restriction. ICNIRP explains that 6 minutes is used as the time averaging period for local thermal exposure assessment as a conservative averaging time for steady state temperature rise in local exposures [3]. Nasim and Kim report that 5G downlink RF fields produce much higher power density (PD) and specific absorption rate (SAR) than their baseline legacy cellular system (which they model as a 3GPP Release 9 system) [12].

3. EFFECTS OF 5G RF-EMF ON NEURONAL EXCITABILITY AND SYNAPTIC FUNCTION

A recent systematic review of in vitro mammalian-cell studies found that the majority of studies did not find statistically significant RF-EMF genotoxic effects, and most of the studies that reported positive results were of moderate-to-low quality [13]. Since any RF-induced cellular effect is likely to be small, in vitro 5G studies are based on exposure systems that maintain the electromagnetic and biological conditions stable and well-characterized [14].

Using live-cell molecular readouts (BRET) in human skin cells, a 24h exposure to a 5G RF-EMF signal at 3.5 GHz, under the conditions tested in this study, no conclusive evidence for the occurrence of molecular effects could be obtained [15]. In another 3.5 GHz in vitro study, results supported the conclusion that 5G RF-EMF up to 4 W/kg did not cause oxidative stress or affect the efficiency of DNA repair in human skin cells [16].

One of the studies specifically focused on testing the effect of a 26.5 GHz 5G electromagnetic field on key biological endpoints under higher-band 5G (FR2) exposure in a neuron-relevant human model (Sannino et al., 2025). In the same conditions of the experiment, RF exposure of SH-SY5Y human neuroblastoma cells during 3 h at 26.5 GHz could not influence cell-cycle progression or cause DNA damage [17].

4. HUMAN NEUROPHYSIOLOGICAL AND COGNITIVE-PERFORMANCE ENDPOINTS IN EXPERIMENTAL EVIDENCE RELEVANT TO 5G

One of the aims of a recent systematic review was to assess the relationship between brief exposure to radiofrequency electromagnetic fields (RF-EMF) and cognitive human experimental studies [18]. All the meta-analyses of the said review found no statistically significant difference between RF-EMF exposure and sham exposure on cognitive performance.

The exposure to 3.5 GHz in the regulatory limits did not have an impact on brain activity in healthy young adults in a controlled-randomised human EEG study [7]. A randomized triple-blind crossover study revealed that even 26 GHz exposure, which was at the 2 V/m level, induced no impact on human brain electrical activity in conditions of regulatory compliance [19]. A pilot study was a randomized, cross-over, triple-blind study that implied that the exposure to 3.5 GHz signals could potentially influence the temperature of the head and neck, which showed a slight rise in this parameter [20]. Short-term 5G mobile phone electromagnetic exposure in a randomized controlled pilot study did not result in any detectable corticospinal or intracortical excitability changes [21].

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5. INTERPRETING 5G NEURO AND COGNITION-RELATED FINDINGS FOR HEALTH AND SAFETY PRACTICE

According to the 2020 radiofrequency guidelines of ICNIRP, their primary purpose is to set exposure limits that will ensure a high level of protection to all people against proven adverse health effects [3]. Jamal et al. reported that in a pilot study at the first deployed 5G band (3.5 GHz), the results were significant but still within the normal physiological range and could be attributed to an uncontrolled variable [20].

An up-to-date review of RF fields over 6 GHz found no evidence that low-level exposures (under ICNIRP occupational limits) are harmful to human health [22]. The same review specifically suggests that future experimental research should enhance the quality of design, especially focusing on the dosimetry and temperature control. As mentioned, ICNIRP also adds that its guidelines will be revised and updated periodically as new developments are achieved in the relevant scientific knowledge [3].

6. EFFECTS OF 5G NETWORK ON MENTAL PERFORMANCE

Available scientific evidence on the effects of 5G technology on cognitive processes and mental health suggests that the evidence available does not support the presence of adverse effects on health-relevant cognitive functions at exposure levels within internationally defined limits [23]. The initial human study that was laboratory-controlled and investigated the impact of 5G signals at 3.5 GHz on the electrical activity of the brain did not reveal statistically significant differences in the power of brain waves in healthy young adults, indicating that exposure to 5G signals at this frequency does not cause any changes in the basic patterns of cerebral activity [7]. Even though some experimental studies on animal nervous systems have reported bioeffects, including the change in neuronal firing frequency, these findings have typically not been independently validated and are commonly linked to methodological limitations in temperature control during the experiments [22]. Although scientific committees have stated that there is no evidence of a direct effect on cognition, a section of the expert community still recommends caution because of the possible correlation between continuous exposure to radiation and neurological disorders and learning and memory deficits [24].

One area of research has specifically been aimed at the study of electroencephalograms (EEGs) when exposed to 5G signals, as an objective measure of central nervous system activity. The study by Jamal et al. [7] was a randomized controlled study where healthy volunteers were subjected to a 3.5 GHz signal, which is one of the main frequencies of the 5G network in the so-called FR1 band. The outcomes of the research revealed that there were no statistically significant differences in the spectral power of alpha, beta, theta, and delta waves, as well as in the total EEG power, which meant that there were no acute effects on the spontaneous electrical activity of the brain in the waking state [7]. These results indicate that the exposure to 5G frequencies, which are not much different than the frequencies of the past generations of mobile networks, does not cause instant disturbances in the cerebral activity that can be observed with the help of conventional neurophysiological techniques [23].

Research at higher frequencies above 6 GHz remains in its infancy as far as cognitive performance is concerned, such as attention, memory, or reaction time. A literature review of the millimeter waves reveals that despite the fact that a specific number of biological reactions have been reported

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in the in vivo studies, the findings are not uniform and do not necessarily imply the impairment of the cognitive processes in humans [22]. Nevertheless, according to a study by the European Parliament (2021), lower 5G frequencies (up to 3.6 GHz) have been explored in the context of previous technologies (2G-4G), with some animal experiments indicating that the frequencies may have neurological effects, and at higher frequencies (26 GHz and above) sufficient human studies are still absent to confirm or disprove the impact on complex mental processes [25].

Besides direct biological measurements, the scientific literature emphasizes the significance of the precautionary principle because of the establishment of constant and omnipresent exposure to EMF by the 5G network through the increase in the number of antennas [26]. Part of the expert community is justified in its concern that the cumulative effects of continued exposure, even at lower levels of radiation than are prescribed internationally, may be on the neurological development and mental health of vulnerable populations, such as children, which explains the necessity of long-term observational studies [24]. Meanwhile, the review of media coverage shows that controversies in the popular press tend to outweigh existing scientific data, assigning to 5G technology a vast spectrum of adverse effects, including carcinogenicity, and serious neurological effects, which only increases the pressure on psychology and the perception of risk among the population [27].

7. CONCLUSION

The end of the study on the effects of the 5G network on mental performance and overall human health can be summarized with several main scientific stances. Conclusive laboratory-controlled human studies (especially concentrating on frequency of 3.5 GHz) have so far demonstrated that under environmental and regulatory exposure levels, there are no acute alterations in brain electrical activity (EEG) in healthy young adults when exposed to 5G cell sources. Scientific reviews of literature exploring frequencies above 6 GHz (millimeter waves) confirm that there is no validated evidence at the present to indicate that these low-level RF fields cause any harm to human health. Moreover, the existing international guidelines [3] offer safeguards against all established adverse effects, whether the exposure is acute or chronic.

Conversely, even with such findings, there remains a great level of doubt and skepticism among the scientists. The review of the literature available suggests that studies on frequencies above 24 GHz (FR2 band) remain insufficient in humans as well as in animals, thus making it impossible to make a conclusive safety evaluation of these particular ranges. Independent scientists point to the presence of bioeffects under laboratory conditions not associated with heating of tissues, and caution about the possible accumulating risks of the dense network of transmitters necessary to support 5G technology. The critical analysis of the existing literature reveals that numerous experimental studies demonstrate that biological reactions to exposure occur, yet the outcomes of such studies are not always consistent and methodologically sound, which is why the design of future studies should be enhanced.

Most reports conclude that, despite the fact that current scientific evidence does not substantiate the allegations of direct harm from 5G networks on cognition and mental health, there is a need to conduct long-term epidemiological surveillance of the population and to exercise the precautionary principle until the existing knowledge gaps about millimeter waves are addressed. Current differences in the understanding of scientific data are usually followed by social polarization and media misinformation, which only adds to the significance of open communication of scientifically based facts to the population.

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