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Review

The Potential Impact of a High-Frequency Telecommunication Network on Cognitive Functions: A Review

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Abstract: The latest cellular technology, known as 5G-NR, is intended to significantly speed up and improve the effectiveness of wireless systems. A revolution in the telecom industry has been sparked by the widespread use of and increased reliance on cellular communication technology. Moreover, 5G and B5G technologies are expected to utilize an even higher-frequency range to achieve faster data transmission and lower latency communication. Consequently, while transmitting signals across various types of equipment and infrastructure, the general public is exposed to much higher frequencies of electromagnetic radiation. The increasing need for 5G NR base stations (gNodeB) has heightened public anxiety over potential negative health impacts. This study reviews recent research on the effects of electromagnetic waves on humans, particularly focusing on how these effects influence cognitive functions. Most research to date has not found significant differences in cognitive performance due to ubiquitous mobile communications. However, current research has largely been limited to 4G technologies, and the health effects of exposure to 5G user equipment (UE) and base stations in higher-frequency bands remain unexplored. If subsequent research suggests that exposure to high-frequency wireless networks significantly impacts cognitive functions, the deployment and acceptance of these technologies may face challenges and constraints. Therefore, such investigations are crucial for determining whether next-generation technologies pose no risk to individuals.

Keywords: base station exposure; public health; RF-EMF; high frequency; cognitive function; UE

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1. Introduction

Since the inception of cellular technology, subsequent generations have been designed to address the drawbacks of earlier generations [1]. However, 5G is not just an improved version of 4G; rather, it is an altogether new technology that will be deployed alongside the global distribution of 4G (LTE-A) networks [2]. The design and implementation of 5G architectures, operations, and core protocols will rely heavily on the usage of a large span of spectrum known as the mm-wave frequency range, together with various other new advancements. As a result, 5G technologies are expected to offer a more reliable and trustworthy user experience [3]. Even 5G and B5G can enhance the overall concept of a smart environment in terms of the reliability of operations. In order to establish a reliable smart environment in the context of wireless technologies, it is imperative for some major domains to intersect: ubiquitous computing ability, intelligent systems and operations, improved facilities for humans, and minimal hazardous conditions for human health. The seamless integration of intelligent devices into everyday routines should be characterized by system updating facilities, integration of new technical standards, and a lack of disruption [4]. The ability to perform flexible computations facilitates a seamless interaction among UE, base station, and all the other components included in the concept of a smart environment. The anticipated high-frequency bands that are proposed from 3GPP recent releases might play a crucial role in establishing reliable telecommunication operations and facilitating the concept of a smart environment.

On the other hand, there is confusion regarding the possible health complications due to higher-frequency bands. The widespread installation of telecom towers and base stations in recent years has raised public anxieties about the inherent health impacts of energy emitted by these infrastructures. Concerns about the negative effects of higher-frequency spectrum on human health could potentially obstruct the implementation of 5G basic infrastructure. The high-frequency bands will be used to establish a condensed network of small picocells, which will lead to the deployment of numerous new transmitters and base stations [5]. The requirement for very high throughput in 5G may lead to a small rise in the transmission power level at the user's end, depending on the frequency level, which might also increase the electromagnetic radiation exacted on the general user in the proximity [6,7]. On top of that, as the frequency of electromagnetic fields (EMFs) rises, the surface absorption can result in more concentrated energy in the skin, perhaps generating localized heating effects and stress within the cells [8]. While the direct impact of higher-frequency radiation on human health remains under study, preliminary research suggests that certain biological responses might influence neurological signaling pathways, potentially impacting cognitive functions [9,10].

Interestingly, a decrease in cell size does not always correspond to higher radiation exposure. Radio link architecture includes a target received power level, and reducing cell size typically leads to a corresponding decrease in downlink transmit power. As a result, a smaller cell size allows for lower transmit power in the uplink, reducing radiation exposure [11]. Moreover, the uplink power poses a potentially higher risk compared to the downlink. This is attributed to the inherent characteristic of downlink power, which naturally diminishes significantly due to substantial path loss. Despite the lower uplink transmit power, when the phone is held in close proximity to the body, minimal path loss occurs, resulting in exposure to a substantial portion of the transmitted power. EMF usually has a stronger probability of penetrating greater depth into the human organs because of the increasing amount of electromagnetic radiation [12]. The majority of earlier studies have only focused on the uplink, but due to changes in the mm-wave 5G coverage exposure region, the downlink may also be dangerous for human health [13]. The consequences of radio frequency electromagnetic energy (RF-EMF) emission on cognitive functions and physiological parameters of individuals have been examined in a number of studies. They mainly concentrate on wireless communication technologies, including BS antennas working in various frequency bands [14,15] and UE [16].

Inconsistent findings from available studies leave it uncertain at this stage whether the RF-EMF field emitted by mobile phone base stations (MP BSs) has any impact on long-term well-being. However, researchers have explored the health impacts of RF-EMF caused by 5G candidate frequencies, ranging from 6 to 100 GHz, on different biological structures [17]. Furthermore, a recent study revealed that 5G radio waves, due to the spatially dense transmitters, pose a risk to human health, underscoring the urgent necessity for further research in this domain [18]. On the other hand, another recent research study has supported the notion of reduced radiation in 5G networks [19]. These findings hold promise for enhancing the safety and reliability of future networks, including 6G. The study also advocates for a paradigm shift toward creating safer, environmentally conscious communication networks and calls for updating safety regulations to align with current radiation exposure levels in our environment. As a consequence of multiple conflicting research findings, this has become crucial for determining whether 5G and B5G technologies are genuinely safe for users. The main contributions and objectives of this review article are as follows:

- To provide categorical information on RF-EMF exposure from UE and base stations.

- To present a comprehensive review of the impact of high-frequency communication technologies on human cognitive abilities.
- To discuss the challenges and opportunities of implementing the smart environment in parallel with the deployment of high-frequency infrastructure.

The article is organized as follows. Section 2 outlines the detailed methodology employed in this study, ensuring a robust approach. In Section 3, a comparative analysis of the findings is presented, enabling insightful comparisons, limitations, future scopes, and observations. Finally, Section 4 concludes the paper.

2. Materials and Methods

This review considers scientific studies that employed various frequency ranges used for cellular communication networks (base stations, UE) as the source of exposure. Upon compiling diverse publications on the health impacts of higher-frequency bands exploited in telecom technologies, a preliminary selection is obtained depending on the title, abstract, and introduction. There were a total of 34 different research studies that were identified to investigate the effect RF EMF has on cognitive functions; they were published between 2005 and 2023. However, 24 of them were finally selected for this review, which examined performance indicators for various cognitive activities and pointed out possible results. Then, using full-text analysis, an even more thorough investigation of relevant publications was carried out, with papers considered in accordance with the subsequent inclusion standards: Single or double-blind and stochastic conditions, various cognitive tasks as experimental approaches, and a radiofrequency range associated with BSs and UE, including GSM-based 2G, 3G (UMTS), 4G (LTE), and 5G technologies, were taken into account while performing a comprehensive literature review. Figure 1 shows a generalized methodology that has been followed in the selected literature in this study.

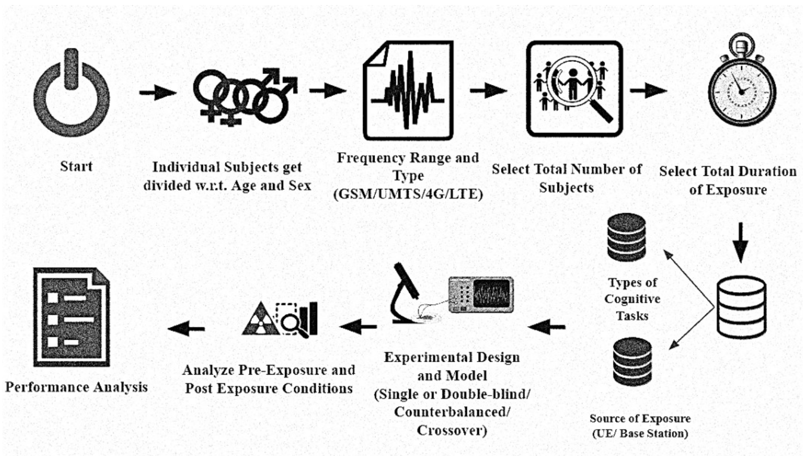


Figure 1. Generalized workflow and experimental setup in the literature.

2.1. Inclusion Criteria

- Research that focuses on how cognitive processes are impacted by high-frequency RF-EMF exposure due to telecommunication networks, particularly mobile phones, UE, and base stations.
- Studies involving human participants of any age.
- Articles presenting novel empirical research, such as experiments, surveys, or clinical trials.
- Studies that evaluate cognitive abilities, utilizing neuropsychological tests or approved assessment instruments.
- Review publications that examine the effects of various exposures on cognitive processes.
- The English language is used throughout the content.
- The study is published only in a journal or conference proceedings.

2.2. Exclusion Criteria

- Studies that do not focus on analyzing the effects of high-frequency exposure emitted from mobile phones, UE, or base stations.
- Studies that focus solely on animal or in vitro experiments.
- Studies that were published in any language other than English.
- Articles that are not published in any journal or conference proceedings.
- Studies that look at how high-frequency RF-EMF exposure affects human physical functions other than cognition.

2.3. Data Analysis

The selected studies were carefully analyzed to determine cognitive activity performance markers and possible conclusions. Full-text assessment was conducted to investigate relevant publications. All of the included research corresponded to a standard method, as shown in Figure 1. This technique serves as a framework for assessing and reporting the study data. Data extraction comprised research variables (e.g., author, publication year, study design), sample size, cognitive functions measurements, UE and base station RF-EMF exposure, and relevant outcomes. Patterns and consistencies among studies were identified and explored to provide a thorough understanding of how high-frequency telecommunication networks affect the cognitive functioning of humans.

2.4. Keyword Strategy and Search Engine

Analogies and alternative words were merged using the Boolean operator to create a number of search sequences: AND narrows and concentrates the search, while OR broadens and expands it. Using Boolean operators like (rf-emf OR base station OR mobile phones) AND (exposure) AND (on) AND (cognitive) AND (function), we were able to narrow down our search on the Scopus database. To find scholarly articles, we looked through PubMed, IEEE Xplore, and ScienceDirect. We chose to restrict the ScienceDirect search results to review articles, scientific papers, and conference papers. Up until the year 2023, research was conducted on all three of the sources (Figure 2). Keywords were used to search for this information in these sources. Boolean operation was employed along with Google Scholar's advanced search. For mobile phone topics and base station-related RF-EMF exposure topics, any of the following three keywords were considered: "Mobile phone exposure" OR "Base station exposure" OR "RF-EMF exposure". For cognitive function impacts and outcomes, the keywords "Human cognitive impact" AND "RF-EMF" are taken into consideration jointly.

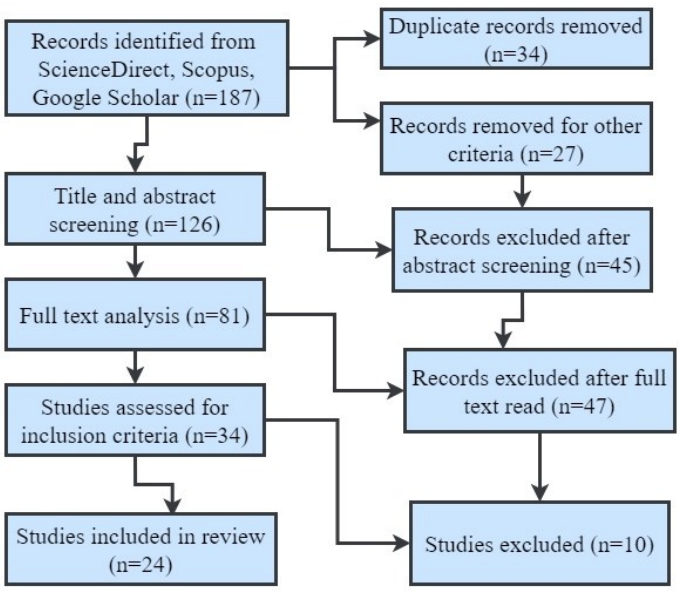


Figure 2. Flowchart for the selection of studies according to PRISMA guidelines [20].

2.5. Cognitive Performance

Cognitive function refers to the cerebral processes and abilities required for acquiring, interpreting, preserving, and utilizing information. It is also connected to the mental skills required for processing and utilizing information, including attention, memory, problem-solving, and creativity, which play a crucial role in activities, such as reading, writing, decision-making, and critical thinking, and are influenced by genetic and environmental factors, such as higher-frequency signals emitted from wireless devices [21]. To find out how radiation from MPs and BSs influences cognitive performance, several studies have employed behavioral assessments, as shown in Figure 3 (note that the magnetic field (**F**), E-field orientation (**E**), and EMF propagation direction (**k**) are all indicated in Figure 3b, adapted from [22]). In the range of circumstances, variables comprise the task response time, consistency, and precision.

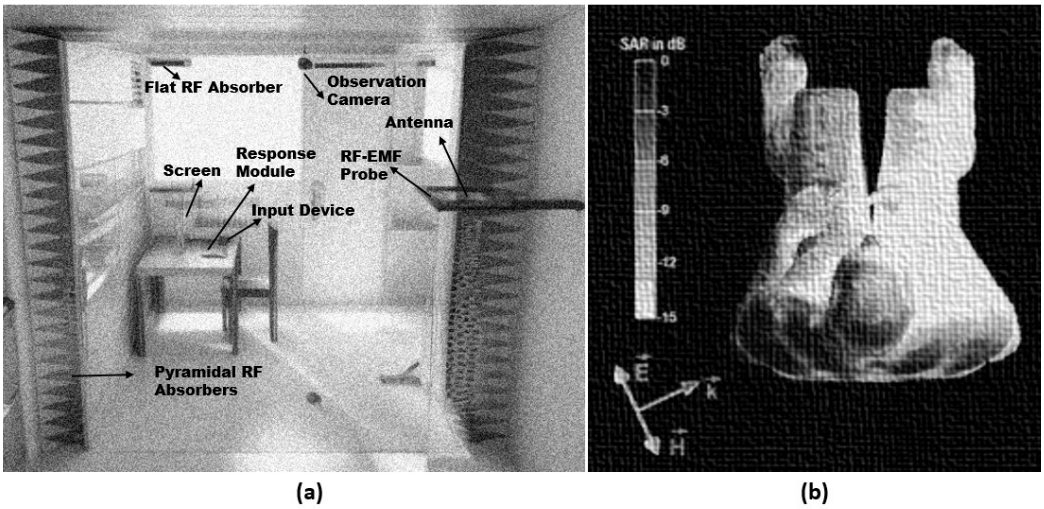


Figure 3. (**a**) Exposure chamber, (**b**) RF-EMF exposure on a male subject in a sitting position (top view) [22].

2.5.1. Limited or No Negative Impacts on Cognitive Abilities

Malek et al. explored the impact of short-term exposure to GSM and UMTS cell phone base station signals on the cognitive performance of 200 Malaysian subjects. The study found that there were no significant negative impacts on the cognitive performance or heart rate for both normal and sensitive subjects, indicating the absence of association and link between EMF exposure and potential negative health consequences [23]. However, the study only examined short-term exposure and did not examine the impact on specific cognitive functions or long-term exposure. Therefore, the results are limited and cannot be generalized to other cognitive functions or long-term exposure.

Regel et al. conducted another separate experiment to investigate the impact of pulse-modulated and continuous-wave RF-EMF on cognitive performance and brain activity in 24 healthy young men [24]. The study found that exposure to this type of RF-EMF signal for 30 min at a precise absorption rate of 1 W/kg reduced reaction time and improved reliability in a working-memory test. The authors deduced that pulse-modulated RF-EMF has a non-thermal biological effect on cognitive performance and specific brain activity, but the underlying physiological mechanisms are still unclear. The study also emphasized the necessity for a valid tool to appraise the specific impacts of RF-EMF exposure on cognition.

Besset et al. examined the consequence of daily MP (mobile phone) usage on cognitive performance in a sample of 55 people, half of whom kept their MPs on and the other half who left them off. The 45-day study included daily exposure to a 900 MHz wave pulsed at a frequency of 217 Hz for two hours. During the study, the participants were subjected to a neuropsychological test consisting of 22 tasks that observed four neurocognitive sub-categories. Despite the absence of a statistically meaningful interaction between exposure and the allocated time frame, the findings indicated that the MP exposure had no impact on cognitive performance following a 13-h rest period [25]. The study concluded that daily MP use does not have a medium-term effect on cognitive function. However, the study's limitations prevented the assertion of any effects from longer exposures.

Movahedi et al. investigated the impact of electromagnetic waves created by 3G and 4G (LTE) cellular phones on cognitive skills, specifically reaction time and short-term memory, in a sample of 85 medical students aged 18–22 years. The findings indicated that exposure to electromagnetic waves resulted in a slower response time among the students, whereas no significant effect was observed on short-term memory [26]. The study further recommended that the frequency of electromagnetic waves might be responsible for the slower response time to stimuli.

Vecsei et al. [27] recently discovered short-term RF exposure from current-generation cellphones. In a double-blind and randomly balanced study, the authors looked into the impact of 3G and 4G radio frequency EMF exposure on the usual cognitive abilities indicated in the Stroop test analysis. The study included 60 young adults who were in decent health (34 for 3G UMTS and 26 for 4G LTE). The Stroop test, however, demonstrated that these frequency signals did not significantly influence the executive function measures, speed of processing, or selective attention. Thus, UMTS and LTE exposure had no discernible influence on the attentional processing metrics found in the Stroop test.

Sauter et al. investigated the potential effects of electromagnetic fields (EMFs) emitted by mobile phones on cognitive functions. Their research focused on assessing the impact of GSM 900 and WCDMA signals on attention and working memory in a group of 30 young male subjects. The study design was well-controlled, employing a balanced, randomized, and double-blind methodology to ensure accurate results [28]. The findings of the study revealed that there was no evidence to support the notion that EMFs from mobile phone signals had an effect on human cognition. The results did not demonstrate any significant influence of GSM 900 and WCDMA signals on attention or working memory in the participants.

There are numerous review articles and surveys available on this topic. To our knowledge, this research represents the first attempt to establish a correlation between the expansion of telecommunication networks, their impact on human cognitive capacities, and the potential for smart environment implementation. Table 1 outlines the focus area of our work in comparison to previous related review articles.

Table 1. Previous relevant review works.

Reference	Focus Area
[29] (Regel et al., 2011)	The review identifies the effects of RF-EMF exposure on cognitive performance measures in humans and highlights the methodological issues in the studies.
[30] (Zhang et al., 2017)	This review article focuses on recent neuroimaging and electroencephalography studies to present a more specific analysis of the effects of mobile phone EMF exposure on neurocognitive functions.
[31] (Benke et al., 2022)	This systematic review aims to assess the impact of long-term radiofrequency exposure on cognitive function by analyzing human observational studies. The review categorizes outcomes into three main areas: global cognitive function, domain-specific cognitive function, and clinical diagnoses of cognitive impairment.
[32] (Ishihara et al., 2020)	The paper reviews previous studies that investigated the relationship between exposure to radiofrequency electromagnetic field (RF-EMF) in the high-frequency band and cognitive function in children and adolescents.
This work	This study categorizes RF-EMF exposure levels from UE, MP, and base stations and investigates their potential impact on human cognitive abilities. Additionally, it explores the association between RF-EMF exposure and the concept of smart environments, highlighting both opportunities and challenges.

2.5.2. Methodological Challenges and Inconsistent Findings in Research

Regel et al. analyzed 41 studies examining the impact of RF-EMF radiation on cognitive functioning in human beings [29]. They found that the lack of standardized methods in bio-electromagnetic research may have contributed to the high variety of findings [29]. These methodological issues include differences in samples and population size, experimental design, and exposure conditions. The authors also claimed that a reliable tool for assessing changes and fluctuations in cognitive functions due to RF-EMF exposure is yet to be developed. In the future, studies should concentrate on identifying a consistent exposure protocol and sensitive tasks to measure the implications of RF-EMF on cognitive performance, particularly in kids. Furthermore, it is crucial to explore the long-term consequences of RF-EMF exposure on human brain activity. Regel et al. conducted another controlled exposure experiment to investigate the effects of signals similar to those from UMTS base stations on generalized cognitive function in healthy people with and without self-reported RF-EMF sensitivity [22]. The study employed a randomized, double-blind crossover design, exposing participants to 45-minute weekly sessions at 0, 1, or 10 V/m electric field strength. The results indicated no substantial association between exposure levels and well-being or perceived field strength in both groups. Additionally, the authors observed only two marginal effects on cognitive performance at 10 V/m, and peak spatial absorption was significantly lower in brain tissue than while using a cell phone. Overall, under the specified exposure levels, the study found no indication of a deterministic link between RF-EMF and detrimental cognitive effects. Rongen et al. conducted experiments to examine the implications of EMF generated by mobile phones on human cognitive performance [33]. The authors concluded that being exposed to signals of the GSM type did not lead to any harmful effects on health, and some studies even suggested that it may improve cognitive performance in adults and children [33]. Zhang et al. reviewed recent studies that examined the possible impact of RF-EMF released from cell phones on human cognitive abilities [30]. While previous research suggested no significant short-term impact on cognitive function, newer studies revealed potential detrimental effects correlated with mobile phone EMF exposure. These effects include an increase in cortical excitability in certain brain regions, which may lead to a faster reaction time. However, there are inconsistencies in the findings, and the impacts of longer-term EMF exposure released by mobile phones on brain function remain unclear. The authors conclude that more prominent research findings are required to fully understand the functional implications of the observed results of MP EMF exposure on human cognitive capacities. Thomas et al. carried out a study to examine the implications of MP exposure on human cognitive performance in teens over a year [34]. The authors found that an increase in exposure to SMS and voice calls was correlated with fluctuations in cognitive response time, but only in participants who had lower usage at the beginning of the study, indicating that these fluctuations may be the result of statistical regression to the mean rather than cell phone radiation. The Stroop color–word test did not reveal any associations with mobile phone exposure. In a study, Eliyahu et al. examined how the electromagnetic radiation from a typical GSM phone at 890 MHz affected people's cognitive abilities. The motivation of the study was to identify the relationship between exposure to a particular brain region and the cognitive processes connected to that region [35]. The findings demonstrated that exposure toward the left side of the brain led to a delayed left-hand reaction time in three of the four cognitive tasks, with just one of the tests being highly significant. However, further research is required to cross-check these findings and resolve the discrepancies between this study and earlier research that produced contradictory or null results. The study emphasized the importance of investigating exposure methodology, responding hand, exposure time, and cognitive tasks as potential factors in future studies. Guxens et al. conducted a large population-based cohort study to examine the relationship between various sources of RF-EMF exposure and cognitive function in children aged 5–6 years [36]. The study specifically focused on residential RF-EMF exposure from mobile phone base stations, the presence or absence of indoor sources of RF-EMF, cell phone use, and cordless phone use. The results of the study showed inconsistent associations between different sources of RF-EMF exposure and cognitive functions. While higher residential RF-EMF exposure from mobile phone base stations was found to be associated with reduced vasomotor coordination, there was no consistent association observed between RF-EMF exposure from other sources (such as cordless phone base stations, Wi-Fi at home, personal cell phone use, and cordless phone use) and cognitive function in children of this age group [36].

2.5.3. Positive Correlation of RF-EMF Exposure on Cognitive Abilities

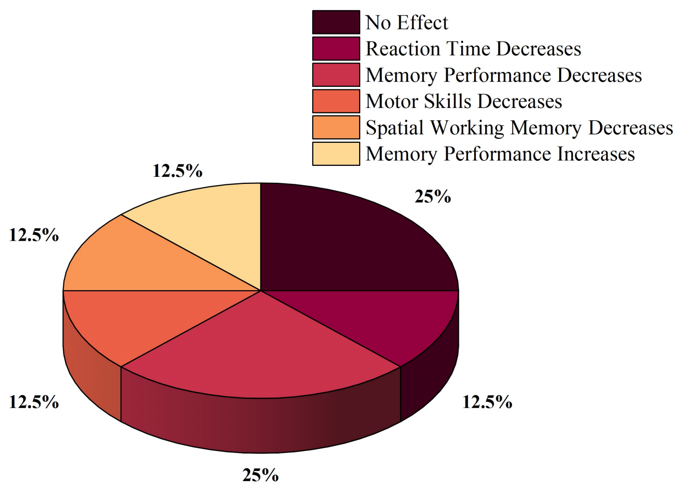
Some research examining the impact of RF-EMF exposure on cognitive abilities has indicated a positive correlation between exposure and certain cognitive functions. Several studies have found evidence suggesting that RF-EMF exposure may have harmful effects on cognitive abilities. These findings somehow validate the assumption that RF-EMF exposure is detrimental to cognitive functions. Table 2 shows the detrimental correlation of RF-EMF with cognitive abilities.

Table 2. Detrimental impacts reported in the literature.

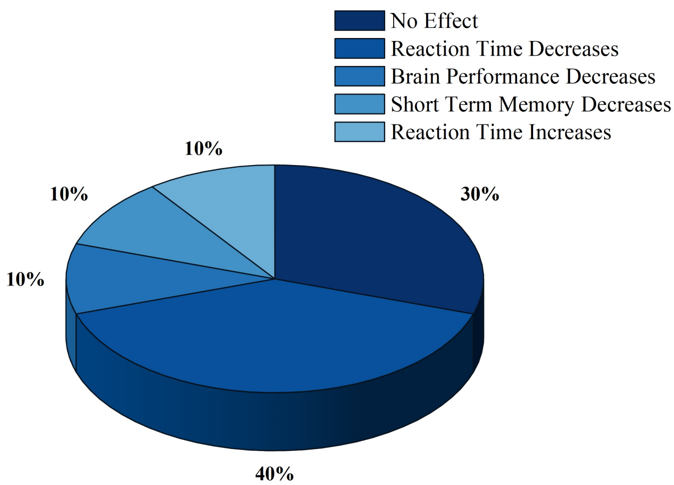
Reference	Study Population	Exposure Source	Tests	Results/Conclusion	Remarks
[37]	439 adolescents	Various wireless devices	Memory performance scores	RF-EMF exposure may impair adolescent memory function	Further research needed for longer exposures
[25]	55 people	Mobile phones	Neuropsychological tasks	No medium-term effect of daily mobile phone use on cognitive function	Additional research required for long-term exposures
[38]	A total of 317 grade pupils	Mobile phone use	Exposure questionnaires	Increased mobile phone use linked to quicker and less accurate responses to cognitive tasks	Further research needed on cellphone use and cognitive function
[34]	Not specified	SMS and voice calls	Cognitive response time	Fluctuations in cognitive response time associated with SMS and voice call exposure	The study relied on self-reported mobile phone use, which may not be accurate or reliable
[35]	Not specified	Typical GSM phone	Cognitive tasks	Exposure to specific brain region delays left-hand reaction time in cognitive tasks	Further research needed for validation
[39]	A total of 18 participants	3G UMTS-based phones	Health symptoms, cognition	No negative effects of 3G phone RF-EMF on sleep and cognition	Study involved a small sample size and short exposure duration
[26]	A total of 85 medical students	3G and 4G cellular phones	Reaction time, short-term memory	Electromagnetic waves affect response time, no effect on short-term memory	Further investigation into wave frequency's impact needed
[40]	Not specified	RF waves from gadgets	Brain signal measurements	RF signals may lead to cognitive deficits	More detailed examinations and studies are required
[27]	A total of 60 young adults	3G and 4G RF-EMF exposure	Stroop test	No influence of 3G and 4G exposure on cognitive abilities	Not specified
[41]	Preadolescence and adolescence	Not specified	Neurocognitive tests	Higher RF-EMF exposure associated with lower non-verbal intelligence scores in pre-adolescents	No significant relationship found for other cognitive function outcomes
[42]	123 boys	Environmental RF-EMFs	Neurobehavioral function	Higher RF-EMF exposure linked to lower verbal expression and higher internalizing problems	No significant effect on other neurobehavioral functioning tasks

3. Findings and Discussion

To date, extensive research has not established a solid correlation between the cognitive functions of humans and the RF-EMF exposure emitted from UE and base stations. This lack of evidence reinforces the acceptability of high-frequency deployments in conjunction with a smart environment. With rigorous safety standards and regulations in place, the focus can remain on the transformative benefits that such deployments bring, including increased efficiency, improved connectivity, and enhanced user experiences. Ongoing monitoring and scientific studies continue to evaluate the potential effects of RF-EMF exposure, ensuring the well-being of individuals while promoting the advancements enabled by the integration of high-frequency deployments within smart environments. Many studies have examined the impact of RF-EMF exposure from MPs and BSs on cognitive functions using various behavioral indicators, including reaction time (RT), brain, and memory performance. As depicted in Figure 4, 25% and 30% of studies showed no negative impact due to exposure from BSs and MPs on cognitive activities, respectively. The combined findings of several studies indicated that exposure to BS impaired cognitive function, including the motor screening task, reaction time (RT), memory performance, and spatial working memory (SWM). Figure 4a,b show the relative performance parameters in terms of cognitive function associated with BS and MP. These findings were taken from 17 relevant research articles.



(**a**) BS exposure



(**b**) MP exposure

Figure 4. Impact of RF-EMF exposure on cognitive abilities.

3.1. Evaluating Health Concerns

Ensuring the well-being of individuals in the context of high-frequency deployment within a smart environment necessitates a thorough examination of potential health concerns [43]. While current scientific knowledge does not provide conclusive evidence linking RF-EMF exposure from user equipment and base stations to cognitive functions, it is imperative for ongoing research to understand any possible risks comprehensively. An extensive review of the available literature reveals a compelling finding: approximately 57% of the studies indicate that exposure to RF-EMF emitted from the UE or base stations has been associated with one or more detrimental effects on cognitive functions.

These findings raise significant concerns about the potential impact of RF-EMF exposure on cognitive abilities and underscore the need for further investigation and precautionary measures. Figure 5 shows the relative impact on human cognitive functions from the current accessible research works.

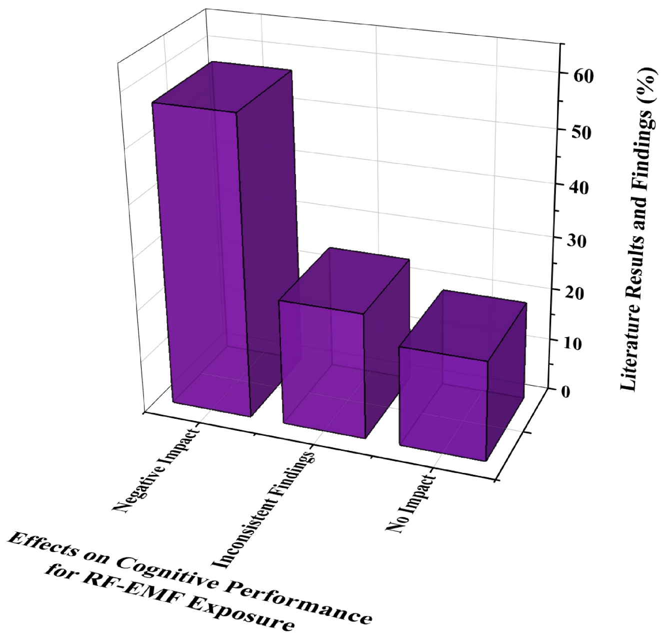


Figure 5. The overall impact of RF-EMF in accordance with existing literature.

It is important to acknowledge that there is some inconsistency in the findings, with around 24% of the studies yielding mixed or inconclusive results regarding the impact on cognitive functions. These variations in findings highlight the complex nature of the subject and the importance of conducting additional high-quality research to gain a comprehensive understanding of the relationship between RF-EMF exposure and cognitive effects. While a portion of the literature reports no significant impact on cognitive functions, accounting for approximately 19% of the studies, it is crucial to interpret these findings with caution. Research in this area is ongoing, and it is essential to consider the overall body of evidence and the potential long-term effects of RF-EMF exposure. Regular updates on scientific findings and risk assessments are essential to inform the public about the latest developments in this field. It is important to emphasize that while health concerns are carefully evaluated, the integration of high-frequency deployments in smart environments has brought numerous benefits to society. From improved connectivity and enhanced data transmission to more efficient services and greater convenience, these deployments have revolutionized various sectors, including healthcare, transportation, and energy management [44]. Therefore, it is crucial to strike a balance between innovation and safety, leveraging advancements while proactively addressing any potential risks through evidence-based research, regulation, and responsible practices. While there is currently no definitive evidence linking cognitive functions to RF-EMF exposure, ongoing research, adherence to safety standards, and open dialogue are essential for addressing any potential risks. By prioritizing public health and safety, while fostering technological advancements, we can create smart environments that are both innovative and safe for everyone.

3.2. Comparative Analysis

After analyzing 24 literature sources on the topic, it can be concluded that there is no solid correlation in the statements of the literature. The experiments were conducted with varying numbers of samples, slightly different experimental setups with similar methodologies, and different age groups, which makes it difficult to draw a definitive conclusion. Additionally, the frequency ranges analyzed in the same GSM (Global System for Mobile Communications) or UMTS (Universal Mobile Telecommunications)-based analysis also differed in these articles. As a result, further research with standardized experimental protocols and consistent sample sizes is needed to provide a clearer understanding of the potential correlation between exposure to MP/BS (mobile phone/base station) emitted electromagnetic radiation and cognitive performance. It can be observed that, for different types of exposure, such as GSM, UMTS, or LTE (long-term evolution), there is a lack of consistency in the concluding remarks for all the selected articles. Furthermore, there is no significant correlation as there are no solid statements provided in all of these articles. Table 3 describes the comparative analysis of the articles that have been reviewed in this paper.

Table 3. Overview of relevant literature in terms of cognitive effect.

Publication Year	Related Works	Exposure Type	Source of Exposure	No Impact	Detrimental Impact	Inconsistent Impact
2015	[37]	GSM and UMTS	UE	×	×	×
2011	[29]	GSM and UMTS	MP	×	×	×
2006	[22]	UMTS	BS	✓	×	×
2019	[45]	GSM	BS	×	✓	×
2009	[33]	GSM	MP	✓	×	×
2017	[30]	GSM	MP	✓	✓	✓
2015	[23]	GSM and UMTS	BS	✓	×	×
2007	[24]	GSM	MP	×	✓	✓
2005	[25]	GSM	MP	✓	×	×
2009	[38]	–	MP	×	✓	✓
2010	[34]	–	MP	×	✓	✓
2006	[35]	GSM	MP	✓	✓	✓
2019	[39]	UMTS	MP	✓	×	×
2019	[26]	UMTS and LTE	MP	✓	✓	×
2013	[40]	GSM, UMTS, LTE	UE	×	✓	×
2018	[46]	GSM and UMTS	UE	×	✓	×
2018	[27]	UMTS and LTE	MP	✓	×	×
2021	[41]	GSM and UMTS	MP	✓	✓	×
2016	[36]	GSM and UMTS	BS	×	✓	✓
2016	[42]	GSM	BS	×	✓	✓
2011	[28]	GSM and WCDMA	MP	✓	×	×
2023	[47]	–	MP	✓	×	×
2022	[31]	–	UE	×	×	✓
2020	[32]	–	MP	×	✓	✓

Notes: "✓" = Positive correlation with the type of impact; "×" = Negative correlation with the type of impact.

3.3. Challenges and Opportunities

The implementation of a smart environment necessitates a balance between the many possibilities it offers and the obstacles it raises. The deployment of high-frequency networks in the pursuit of establishing a green environment presents both opportunities and challenges, particularly in relation to their potential effect on human cognitive functions. On the opportunity side, high-frequency networks enable faster and more efficient device-to-device (D2D) communication and data transmission [48], supporting the integration of various smart technologies and applications that contribute to environmental sustainability. These networks can facilitate real-time network monitoring [49], localization, and control of energy consumption [50], not only in terrestrial but also in underwater environments [51], enabling the optimization of transportation systems and enhancing resource management [52]. This holistic strategy reduces carbon emissions and supports a greener, more environmentally friendly livelihood on land and sea. However, challenges arise when considering the potential impact on human cognitive functions. While existing scientific research has not conclusively established a direct correlation between cognitive functions and high-frequency network exposure, it is essential to conduct further studies to comprehensively evaluate any potential risks. This calls for a balanced approach that prioritizes both environmental sustainability and human well-being.

One challenge is ensuring that the deployment of high-frequency networks aligns with strict safety standards and regulations [53]. Monitoring exposure levels and adhering to established guidelines can help minimize any potential health risks. Implementing safety protocols, such as maintaining safe distances from network infrastructure and utilizing advanced antenna technologies, can further mitigate potential concerns [54]. Another challenge is addressing public perception and fostering trust [55]. Transparent communication, providing accurate information, and addressing concerns openly are vital to building public confidence in the safety of high-frequency networks. Educational initiatives that raise awareness about scientific evidence, risk assessments, and safety measures can help individuals make informed decisions and alleviate any unfounded fears.

Moreover, the equitable deployment of high-frequency networks should be a priority. Ensuring access to reliable and high-speed connectivity for all segments of society, regardless of socioeconomic factors, is crucial to prevent the exacerbation of existing digital divides. Bridging this gap requires collaboration between governments, industry stakeholders, and community organizations to provide affordable and accessible network infrastructure and promote digital literacy. Furthermore, the environmental benefits of deploying high-frequency networks should not overshadow the potential environmental impact of network infrastructure itself. While aiming for a greener environment, it is important to consider the energy consumption and sustainability of network infrastructure components. Implementing energy-efficient practices, utilizing renewable energy sources, and adopting responsible waste management strategies can help mitigate any adverse environmental effects [56].

Hence, deploying high-frequency networks to establish a green environment presents opportunities for environmental sustainability and resource management. However, challenges related to potential effects on human cognitive functions must be carefully addressed through ongoing research, adherence to safety standards, and open communication. Balancing environmental benefits, public health, and equitable access to connectivity will be key to successfully deploying high-frequency networks in a responsible and sustainable manner.

3.4. Limitations

Several limitations are observed in studies examining the effects of RF-EMF exposure on cognitive functions and memory. Some common limitations in the literature are as follows:

- Small sample size: Several studies have been carried out with a small sample size, which may restrict the findings' generalizability for larger groups.
- Reliance on self-reported data: Some studies included self-reported data on wireless device usage, which may be prone to recall bias and may not adequately reflect real exposure levels.
- Short-term measurements: Some studies only tested memory performance or cognitive functions over a short period of time, which may not reflect the long-term effects of RF-EMF exposure.
- Absence of validated assessment methods: The inconsistent nature of study results may be attributed to the lack of proven methods to accurately detect variations in cognitive performance caused by exposure to RF-EMFs.
- Technical variations: Differences in sample size, study group, design of experiment, exposure setup, and exposure environments may all contribute to the broad variation of findings.

- Heterogeneity of participants: The majority of investigations featured right-handed subjects, and possible variations in response among various groups of participants might need to be examined thoroughly.
- Absence of specified sensitive tasks: No specific task that is exceptionally sensitive to RF-EMF exposure has been identified.
- Limited research of long-term impacts: Some studies only looked at the short-term effects of RF-EMF exposure; therefore, they are unable to draw any conclusions regarding the long-term effects or the consequences of prolonged exposure on human health.
- Marginal effects: The reported changes in brain function in some research were minor and might have happened by chance, raising doubts regarding their relevance.
- Possible exposure from other sources: The studies did not account for the possibility of exposure to RF-EMF from other sources, such as televisions, remote controls, and wireless networks.
- Variations in the preliminary assessment of exposure: Studies showed variations in the initial assessment of exposure, which could lead to variation in the outcomes.

3.5. Toward Sustainability: Net Zero and Edge Intelligence in High-Frequency Contexts

The primary aim of net zero operations is to achieve a state of zero environmental impact and carbon footprint when initiating projects or introducing technological advancements [57,58]. The alignment of net-zero goals with future higher-frequency network deployments underscores a commitment not only to technological advancement but also to ensuring user safety [59]. It is crucial to incorporate strict safety precautions, thoroughly study the consequences on cognitive health, and ensure that technological improvements align with net-zero principles. This ensures a sustainable technical landscape that eliminates environmental effects while ensuring human cognitive well-being in high-frequency network deployments. As communities strive towards sustainability, these infrastructures become vital to improved efficiency and inter-connectivity [60].

Another fundamental aspect of high-frequency networks is their reliance on edge computing, a paradigm that revolutionizes data processing by enabling real-time analysis at the network periphery [61]. The integration of edge computing into high-frequency networks presents significant potential for innovation and efficiency, meeting the increasing demand for faster data processing across diverse electronic devices and networks situated closer to the user [62]. To guarantee that edge computing deployment complies with safety regulations, cooperation between technology development and cognitive health research is essential. This approach might help create a technologically sophisticated environment that is both effective and considerate of its influence on human intelligence, guaranteeing a smooth transition of edge computing into high-frequency networks.

On the other hand, integrating artificial intelligence (AI) features at the network periphery to transform instantaneous decision-making, edge intelligence represents an evolutionary advancement inside high-frequency network operations [63]. Without depending entirely on centralized systems, this integration allows for quick data processing and well-informed actions in high-frequency signal circumstances where split-second responses are required [64]. Edge intelligence reduces latency by locally processing and filtering data, ensuring quick and precise responses that are essential for real-time communication networks applications [65]. Furthermore, through the selective transmission of critical information, this integration lowers the strain on network bandwidth and maximizes the efficiency of data processing [66]. Edge intelligence enhances network resilience through its decentralized decision-making process, which empowers autonomous decision-making even during network disruptions [67]. This method eliminates the vulnerability of sensitive data during transmission, which improves security measures and boosts operational efficiency [68,69]. A major step forward, the integration of edge intelligence with high-frequency network operations improves the responsiveness, security, and agility of contemporary data-intensive environments [70,71]. This revolutionary merger changes the game for high-frequency network operations by allowing for a more flexible and efficient network architecture.

3.6. Future Directions

Future research should highlight the development of large-scale longitudinal studies involving different groups to improve our understanding of the possible effects of RF-EMF exposure on cognitive performance. Additionally, it is essential to look into the underlying causes of the apparent inverse relationship between RF-EMF exposure and memory function. It is fundamental to carefully investigate how long-term exposure to RF-EMFs affects cognitive functions. Expanding the duration of research to cover longer time periods will make it possible to assess whether any cognitive impairments linked with RF-EMF exposures persist or alter over time. To determine the generalizability of the reported effects, investigations in multiple populations and across different countries are essential. The relation between exposure to RF-EMF and cognitive performance is complex, and these types of studies can shed light on the influence of societal, environmental, and genetic factors [72]. Furthermore, investigating the prospective effects of RF-EMF exposure on cognitive domains other than memory, such as speech, executive function, and attention, can provide an in-depth understanding of the cognitive effects of RF-EMF exposure. Additionally, more research is required to examine how exposure to RF-EMFs affects people of different ages, including kids and adults. This will aid in the identification of possible age-related vulnerabilities or variations in cognitive reactions after RF-EMF exposure. These research efforts will considerably contribute to a more thorough knowledge of the potential consequences of RF-EMF exposure on cognitive functions, as well as provide direction for the creation of evidence-based guidelines and legislation.

4. Conclusions

Although 5G technology has many benefits and applications, it has become increasingly obvious that considerable detrimental implications to public health could emerge if it is extensively deployed without proper guidelines. The existing radio wave radiation to which we are exposed appears to be hazardous to the biological mechanisms of a human being. This research article represents an overview of exposure experiments carried out with signals ranging from 2G GSM to 4G LTE, specifically in the sub-6 GHz range. The findings indicate that the majority of previous research focused on 2G, 3G, and 4G did not demonstrate any significant impact and lacked consistency in how exposure to these signals impacted the cognitive metrics of volunteers. However, there is a limitation in the literature regarding the effects of exposure to 5G BS transmissions (over 6 GHz, including 24.25 GHz, 54 GHz, and 71 GHz) on cognitive performance in adults. Further research in this area is necessary to fill this knowledge gap. A more in-depth and comprehensive study of hazards to human health and overall implications would be required for sound regulatory policy concerning current and near-future telecommunications initiatives. A more comprehensive understanding of these potential hazards is necessary to guide the development of appropriate regulatory policies and to ensure the safe deployment of green environments in the context of 5G technology.

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Abbreviations

The following abbreviations are used in this manuscript:

BS	base station
D2D	device-to-device
EMF	electromagnetic field
LTE	long-term evolution
UMTS	Universal Mobile Telecommunications System
GSM	Global System for Mobile Communications
WCDMA	Wideband Code Division Multiple Access
MP	mobile phone
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RT	reaction time
SWM	spatial working memory
RF-EMF	radiofrequency electromagnetic energy
SMS	short message service
UE	user equipment
Wi-Fi	wireless fidelity
3GPP	3rd Generation Partnership Project
5G NR	5th Generation New Radio
B5G	Beyond 5th Generation
AI	Artificial Intelligence

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