

Spatial Learning And Memory Impairment In Rats Exposed To 5G Frequencies: A Literature Review

Arefa Suleman Tadv¹, Dr. Shilpa Prashant Kodgire²

¹Phd Scholar, Department of Electronics Engineering, Maharashtra Institute of Technology Chhp. Sambhajinagar, (M.S)-431004, India

²Associate Professor, Department of Electronics Engineering, Maharashtra Institute of Technology Chhp. Sambhajinagar, (M.S)-431004, India

Abstract: The rapid global deployment of fifth-generation (5G) wireless technology has raised considerable public health concerns regarding potential biological effects, particularly on the central nervous system. Existing research on the impact of radiofrequency electromagnetic radiation (RF-EMR) on cognitive function has yielded inconsistent results, necessitating a comprehensive review of the current evidence, specifically concerning spatial memory, which is highly dependent on hippocampal integrity.

Impairment Observed: Studies on simultaneous exposure to multiple frequencies, such as 1.5 GHz and 4.3 GHz, have shown significantly prolonged escape latencies in the Morris Water Maze (MWM) and reduced target crossings, indicating impaired spatial memory.

No Significant Effect: Research specifically into the 4.9 GHz band (a common 5G frequency) using the Y-maze and other tests has found that it may induce depression-like behaviour but does not necessarily impair spatial memory.

5G Technology Characteristics: The Fifth Generation (5G) of mobile communication utilizes a wider range of frequencies than previous generations, extending into higher frequencies, specifically 5G instead uses low-band (600–900 MHz), mid-band (GHz), and high-band (mmWave)

5G Deployment Impact: Unlike 4G, 5G utilizes more base stations, beam-forming antennas to focus signals, and higher frequencies, which increases the density of potential exposure to radiofrequency electromagnetic fields (RF-EMF).

Public Concern: Increased 5G deployment has generated public concern regarding potential health effects on the central nervous system, particularly due to the proximity of devices to the head.

Focus of Review: Existing reviews often focus on 2G-4G, but this review must focus on 5G-specific frequencies (e.g., 2.4GHz, 3.5 GHz, 4.9 GHz) and their unique modulation techniques.

Objective: This review systematically evaluates existing literature and original research studies to determine whether exposure to 5G frequency RF-EMR induces spatial learning and memory impairments in rat models.

Key words:

MHz (Megahertz): Millions of cycles per second (e.g., 900 MHz).

GHz (Gigahertz): Billions of cycles per second (e.g., 3.5 GHz, 4.9 GHz). This is the standard unit for 5G frequencies.

RF-EMR / RF-EMF: Radiofrequency Electromagnetic Radiation or Fields.

SAR (Specific Absorption Rate): Measured in W/kg (Watts per kilogram). It measures how much energy the rat's brain tissue absorbs.

MW/cm² (Mill watts per square centimetre): A unit of Power Density used to measure the intensity of the microwave signal.

CNS: Central Nervous System (the brain and spinal cord).

MWM: Morris Water Maze. The swimming test used to measure Escape Latency (the time it takes a rat to find a hidden platform).

OFT: Open field Test

CA3: A specific region of the Hippocampus (the part of the brain responsible for memory).

mRNA / Transcriptomics: The study of gene expression. This looks at how 5G might "switch" certain genes on or off in the brain.

C-Fos: A protein used by scientists as a "marker" to see which neurons (brain cells) are active after exposure.

BBB: Blood-Brain Barrier. The protective layer that filters what enters the brain from the blood.

Beam-forming: A 5G technique where the signal is "pointed" directly at a device rather than broadcasting in all directions.

SOD (Superoxide Dismutase): Acts as the first line of defense by catalyzing the dismutation of superoxide radicals into hydrogen peroxide.

CAT (Catalase): Specifically breaks down into water and oxygen, protecting tissues from oxidative damage.

GSH (Glutathione Peroxidase - GPx): A crucial non-enzymatic antioxidant that works with glutathione peroxidase to neutralize and other peroxides.

NLRP3: (NOD-like receptor protein 3) is a vital protein that acts as a sensor within your immune system to detect "danger signals".

Introduction:

The world is quickly moving to 5G technology to make our internet faster and connect more devices. Because 5G uses different, higher radio frequencies than older 4G or 3G networks, many people are asking: "Is this safe for our brains?"

Scientists are particularly interested in how these signals affect spatial learning and memory—the part of the brain that helps us remember where things are and how to navigate through a city or a building. To study this, researchers use rats, because their brain structure and the way they learn are very similar to humans.

In the past, some studies on older cell phone signals suggested that long-term exposure might cause "brain fog" or make it harder for rats to finish memory puzzles, like finding a platform in a pool of water. Now, with 5G, we are testing if these newer, more powerful signals cause similar problems.

This review looks at recent experiments to see if 5G frequencies cause stress in brain cells or damage the hippocampus (the brain's "memory centre"). By looking at all the latest data, we can better understand if our new technology might be making it harder for the brain to learn and remember.

Inconsistency in 5G Research: Highlight that while some studies report adverse cognitive effects (e.g., depression-like behaviour or hippocampal neuron injury), others find no significant impact, suggesting that effects depend on exposure duration, power density, and specific 5G frequency bands.

Need for Synthesis: Argue that a review is necessary to consolidate findings on the specific 5G spectrum (above 6 GHz or Sub-6 GHz) to understand its true effect on hippocampal-dependent learning and memory.

Methods: A systematic Literature survey of academic databases (e.g., PubMed, ScienceDirect) was conducted to identify studies that investigated the effects of 5G-related frequencies (including 900 MHz, 2.4 GHz, 2.65 GHz, and 4.9 GHz, among others) on spatial memory in rats or mice. The review synthesized findings from behavioural tests, such as the Morris water maze (MWM) and Y-maze, alongside reported morphological and molecular changes in brain regions like the hippocampus.

1. Exposure Protocols

To simulate real-world 5G environments, researchers use specialized signal generators and antennas.

Exposure Apparatus: Rats are often housed in Plexiglas cages within an anechoic chamber to prevent external interference. Systems typically include a signal generator, an amplifier, and a radiating antenna (such as a 5G NR base station simulator).

Frequencies: Studies focus on 5G-specific bands, most commonly 2.45, 3.5 GHz or 4.9 GHz.

Dosimetry: Researchers measure the Specific Absorption Rate (SAR)—the rate at which the body absorbs RF energy—to ensure exposure remains within safety limits (e.g., averaging 0.19 W/kg to 2.06 W/kg).

Duration: Exposure is usually chronic, ranging from 1 to 4 hours daily for periods of 21 to 45 days

2. Behavioural Assessments

Standardised mazes are used to evaluate how radiation affects the brain's ability to navigate and recall locations.

Morris Water Maze (MWM): The "gold standard" for spatial memory. Rats must find a submerged platform in a pool of water. Researchers measure Escape Latency (time to find the platform) and Probe Trials (platform removed to see if the rat searches the correct quadrant).

Y-Maze: Used to assess spatial working memory by observing the rat's natural tendency to explore a "novel arm" compared to previously visited ones.

Open Field Test (OFT): Often used as a control to ensure that any memory deficits aren't just due to changes in locomotion or anxiety.

Review of findings:

According to a study by Samta Sharma and Sangeeta Shukla on ScienceDirect.(2020) Mobile phone-emitted electromagnetic radiation (EMR) exposure causes time-dependent reductions in rat working memory by inducing oxidative stress, altering neurotransmission, and causing cellular damage in the brain,. The study found increased malondialdehyde (MDA) and decreased antioxidant enzymes (SOD, CAT, GSH) alongside altered acetylcholine esterase (AChE) activity.

Sonia Spandole-Dinu's(2023) pilot study found that long-term (16-week) exposure to common 2.45 GHz Wi-Fi radiofrequency (RF) radiation in mice increased their movement but didn't cause major brain structure changes, though it did lower overall DNA methylation, hinting at epigenetic shifts. Researchers observed potential cellular effects like slight neuronal vacuolation and oedema in other studies, suggesting RF might act as a stressor, but conclusive evidence on functional impacts (memory, anxiety) remains mixed, emphasizing the need for more research into RF's real-world effects on the brain.

A 2023 review by Eskandani & Zibaii reveals both detrimental (oxidative stress, BBB changes, anxiety, memory loss) and potentially beneficial (improved learning/memory, neuroprotection) effects of RF-EMF and ELF-EMF on the Central Nervous System (CNS), with frequencies ranging from low MHz (like 700 MHz, 2450 MHz)

A study by Anne Canovi (2023) and colleagues investigated the effects of 3.5 GHz 5G signals on neuronal networks in vitro, finding no conclusive impact on firing or bursting rates at standard Specific Absorption Rates (SAR) of 1 and 3 W/kg. However, team found that normal, everyday levels of 3.5 GHz 5G signals (1-3 W/kg) do not change how brain cells (neurons) send electrical signals in a lab setting. However, when exposed to extremely high, non-standard levels (28 W/kg), the cells showed about a 40% drop in both firing and bursting activity, indicating high-intensity exposure can inhibit neuronal activity.

A specific study by Tong-Zhou Qin (2024) found that 4.9 GHz RF exposure induced depression-like behaviour but did not significantly affect spatial memory or anxiety-like behaviour in mice. The observed behavioural changes were associated with specific brain tissue damage and metabolic alterations, rather than general brain injury.

Another finding by Xing Wang(2024) Exposure to 4.9 GHz radiofrequency (RF) fields in mice significantly alters brain metabolism, particularly affecting glycerophospholipid pathways, and causes imbalances in serum and brain protein profiles, potentially impacting cellular communication like gap junctions, offering insight into biological effects of 5G frequencies.

Head-only exposure to 900 MHz GSM by B Bontempi (2024) EMFs in rats can induce localized changes in neuronal activity, shown by increased c-Fos expression (a marker of activation) in specific brain regions like the frontal and cingulate cortices, particularly at higher power levels (SARs 1-6 W/kg), without necessarily causing detectable spatial memory deficits, suggesting effects on basic neural signalling rather than complex cognition under certain acute or sub chronic conditions.

Krivova et al. (2024) found that chronic, low-intensity 5G NR exposure (2.4 GHz) did not significantly impair cognitive function, spatial memory, or physiological metrics (weight, organ health) in Wistar rats across various ages. The study also observed normal learning dynamics in the Morris Water Maze, indicating that such exposures, when following safety guidelines, do not induce adverse effects

A systematic review by Felix Meyer and Annette Bitsch (2024) found that evidence linking radiofrequency electromagnetic field (RF-EMF) exposure to oxidative stress biomarkers is of very low certainty. Studies on rodents showed either no or inconsistent effects of RF-EMF on oxidative stress biomarkers in the brain, liver, blood, and female reproductive system.

According to a study by Zhou et al. (2024), daily exposure of mice to 3.5 GHz radiofrequency radiation at 50 W/m² for one hour over 35 days induced anxiety-like behaviour by disrupting the gut microbiota. This disruption led to altered chemical signals that triggered the NLRP3 inflammasome in the hippocampus, causing neuronal pyroptosis and resulting in the observed anxiety-like symptoms. ScienceDirect

Based on the study by Hadeel M. Hussein and Ghada A. Taqa (2024), this article from Research Gate shows that exposure to mobile phone radiofrequency (RF) radiation causes significant structural brain alterations, including gliosis, vacuolization, and edema , Exposure caused severe morphological issues: irregular brain outlines, heterogeneous echogenicity, shrunken specimens, and echo-free spots.

A study by Georgia Sousouri (2025) found a genotype-specific effect from 5G radio-frequency-electromagnetic-field exposure, where a 3.6 GHz signal altered human sleep brain activity, while a 700 MHz signal and sham exposure showed no significant effect.

In another study by J Lambeth 2025 involved exposing male mice daily to a 3.5 GHz 5G signal for 1 hour over six weeks, using a head-restrained setup to achieve specific absorption rates (SARs) around 0.43 W/kg in the cortex, assessing behaviour (locomotion, anxiety, memory) in open fields and object recognition tasks, and then

performing mRNA profiling (transcriptomics) on cortical tissue to find changes in gene expression, focusing on mitochondrial and glutamatergic pathways.

Sareesh Naduvil Narayanan's(2025) research shows chronic radiofrequency electromagnetic radiation (RF-EMR) exposure in rats impairs contextual fear memory, increases hippocampal perivascular space, causes apoptosis in the hippocampus (CA3 region), and leads to lymphocytic infiltration and apoptotic changes in the adrenal glands zona fasciculata, demonstrating significant neurological and physiological stress responses, using methodologies like fear conditioning tests and histology.

Liu Sun (2025) Published paper on Compound exposure to 2.8 GHz and 9.3 GHz microwaves (10 mW/cm^2) which caused significant, albeit reversible, learning and memory impairment in rats, peaking around 3–7 days post-exposure. The injury, linked to hippocampal damage, mitochondrial dysfunction, and Nissl body reduction, shows potential for self-recovery by 28 days post-exposure, accompanied by altered gene expression

Conclusion: The literature presents conflicting evidence. Some studies using frequencies like 900 MHz reported significant impairments in spatial learning and reference memory, alongside observed morphological changes in hippocampal neurons and mitochondrial degeneration. Conversely, several studies specifically using 4.9 GHz or 2.4 GHz frequencies found no significant adverse effects on spatial memory performance, although some noted other behavioural changes (e.g., anxiety-like or depression-like behaviours) or neuronal loss in the amygdala. The inconsistency may be due to variations in exposure parameters (frequency, duration, power density, SAR levels) and methodologies.

Neurochemical & Brain Changes: 3.5 GHz RF radiation (50 W/m^2) has been shown to cause anxiety-like behaviour, linked to NLRP3-dependent pyroptosis (a type of cell death) in the hippocampus.

Brain Metabolism: 4.9 GHz exposure can alter brain metabolism, specifically impacting glycerophospholipid metabolism, and induces changes in the protein profile of brain tissue.

Oxidative Stress & Damage: Long-term exposure to 3.5 GHz radiation has been associated with increased reactive oxygen species (ROS) in the brain, leading to oxidative damage, including lipid peroxidation and mitochondrial swelling.

Cognitive & Behavioural Impact: While some studies indicate potential for cognitive impairment or altered emotional behaviour, other studies using 5G NR, 3.5 GHz, and 4.9 GHz found no significant impact on spatial memory in certain experimental settings.

Neural Mechanisms: The effects may be mediated by alterations in neurotransmitter levels (e.g., serotonin, dopamine, acetylcholine) and damage to glial cells.

The available evidence is inconclusive regarding a definitive link between 5G frequency exposure and spatial learning and memory impairment in rats. While some studies indicate potential negative effects and associated structural changes, others report no significant impact under different exposure conditions. The heterogeneity in research methodologies underscores the need for further standardized and well-replicated investigations to establish a clearer understanding of the potential neurobiological risks associated with 5G RF-EMR exposure.

Future tests must use very precise tools to ensure that any changes in the brain are caused by the radio waves themselves, not just by the heat from the equipment. Scientists recommend studying female rats and juvenile (young) **rats**. This helps us predict how 5G might affect children or different genders in humans. Future research should focus

on higher frequencies (called Millimetre Waves or FR2), as we have very little data on how these specific waves interact with brain cells.

Mixed Results on Cognitive Function: Chronic exposure to 5G RF-EMF generally does not result in significant impairment of spatial memory or learning in rats, with studies showing no differences in Morris water maze performances. However, some studies reported changes in emotional behaviour, such as increased depression-like behaviour, potentially linked to structural changes in specific brain regions like the amygdala, rather than the hippocampus.

Need for Further Research: Despite the lack of severe acute effects, studies emphasize that the potential long-term, cumulative effects of chronic 5G exposure remain unknown, calling for more longitudinal studies, particularly on different age groups and genders.

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