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Future of Machine-to-Brain Communication: Listen Deposits

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ABSTRACT

Brain–computer interfaces (BCIs) offer new avenues for communication and control, but current technologies are limited by low bandwidth, invasiveness, and reliance on traditional sensory pathways. This paper proposes a novel paradigm of machine-to-brain communication using AI-modulated electromagnetic waves to transmit data directly into the brain's neural circuitry. We outline the theoretical basis for this approach, drawing on neuroscience and electromagnetic theory: specifically, how external radiofrequency (RF) signals (in the 5G spectrum) might influence neural activity by modulating the dynamics of sodium ions that underlie action potentials. A concept termed **listenDeposits** is introduced to describe auditory-like perceptual experiences induced without any physical sound, analogous to hearing a "broadcast" directly in the mind. We review background literature on brainwaves, neural signaling, and prior uses of AI in neural stimulation to ground our proposal in existing science. We then present a framework in which AI-driven 5G-wave modulation could entrain neural firing patterns and encode information non-invasively, and we explore how factors like signal amplitude and proximity could enable shared, collective perceptual experiences among groups (a "wireless" group BCI effect). Ethical considerations are discussed in depth, emphasizing the need for transparency, informed consent, and human-centric oversight as this technology develops. Finally, recognizing the speculative nature of our proposal, we outline experimental approaches to validate these ideas in future work- including the use of sodium-sensitive MRI and EEG to detect wave-induced neural synchronization. This paper lays a conceptual foundation for AI-modulated machine-to-brain communication, aiming to inspire interdisciplinary research while underscoring the paramount importance of ethical and safe innovation in this emerging domain.

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Introduction

Brain-computer interfaces (BCIs) have rapidly advanced in recent years, enabling direct communication between neural tissue and machines [1]. Traditional BCIs, however, face significant limitations in both **throughput** and **usability**. Non-invasive interfaces (e.g. EEG headsets) suffer from low spatial resolution and poor signal-to-noise ratios, severely constraining bandwidth for data transfer [2]. Invasive BCIs (implanted electrodes) can achieve higher fidelity but require risky neurosurgery and long-term biocompatibility challenges. Thus, despite decades of progress, most BCIs remain limited in the amount of information they can read from or write to the brain compared to conventional human-computer interfaces (like eyes for reading or ears for audio). In essence, current BCIs provide only a narrow "pipe" to the brain, whereas natural sensory channels handle massive data streams effortlessly. This disparity motivates exploration of new methods to interface with the brain that are both high-bandwidth and minimally invasive.

Another fundamental limitation of contemporary approaches is their reliance on translating machine outputs into perceptible stimuli (visual, auditory, haptic) that the user's senses must still interpret. For example, a device might convey information by displaying images or playing sounds, which the brain then processes via the eyes or ears. This indirect pathway inherently involves latency and loss of fidelity. **Machine-to-brain communication**-directly transmitting data into the brain's own signaling processes – could bypass these bottlenecks. If realized, such a capability would represent a paradigm shift: instead of the brain having to pull information from an external device via our senses, the device would push information into neural circuits in a format the brain can immediately interpret.

Here, we introduce the concept of using electromagnetic (EM) waves modulated by artificial intelligence (AI) as a means to achieve direct data transfer to the brain. The idea is inspired in part by existing neurostimulation techniques. For instance, transcranial magnetic stimulation (TMS) uses time-varying magnetic fields to induce electric currents in specific brain regions, modulating neural activity non-invasively [3]. Likewise, targeted electrical or ultrasonic stimulation can evoke sensory experiences (e.g. phosphenes – perceived flashes of light-via visual cortex stimulation). These technologies demonstrate that external physical stimuli can influence brain activity without implants [3,4]. Our proposal extends this principle from therapeutic modulation to high-bandwidth information transmission: using sophisticated AI algorithms to modulate electromagnetic waves (particularly in the RF spectrum) in such a way that the brain's neurons respond as if they were receiving ordinary sensory input. In effect, the EM waves would serve as an invisible, contactless "carrier" of information into the brain.

A key inspiration for this approach comes from the little-known but well-documented **microwave auditory effect** (also called the

Frey effect). Allan H. Frey's pioneering work in the 1960s showed that humans can perceive sounds (such as a buzzing or clicking sensation) when exposed to pulsed microwave radiation, even though no acoustic sound is present [5,6]. The radiofrequency energy, when delivered in short bursts, interacts with the head and induces auditory perceptions generated entirely within the brain. Notably, later experiments reported that by using "voice-modulated" microwave pulses, subjects could recognize simple words transmitted to them via an RF signal. These findings serve as a proof-of-concept that data in the form of auditory information (spoken words) can be encoded in EM waves and decoded by the human brain without any external receiver [7,8]. The microwave auditory effect is possible because the pulsed energy causes minute thermoelastic expansions in brain tissue, triggering signals in the auditory pathways. While the phenomenon in its demonstrated form was limited to rudimentary sounds and required high-power pulses, it provides a striking example of direct machine-to-brain input. Our work builds on this concept, aiming to leverage modern AI and telecommunications advances (like 5G beamforming and adaptive signal modulation) to greatly enhance the precision, bandwidth, and safety of such EM-based neural communication.

In the following sections, we develop the theoretical framework for **AI-modulated electromagnetic waves** as a channel for machine-to-brain communication. We begin by reviewing relevant background information: the nature of brainwaves and neural electrical activity, the role of sodium ions in neural signaling, and how EM fields interact with biological tissue. We also survey prior applications of AI in optimizing electromagnetic stimuli and neural interfaces, which will inform our approach [9-11]. Next, we focus on the biophysical interaction between 5G-frequency EM waves and neuronal dynamics, proposing a mechanism by which AI-designed waveforms could influence voltage-gated sodium channels and thereby induce patterned neural activity. Our research introduces the concept of **listenDeposits**-subtle auditory-like perceptions implanted directly into the mind-as a potential outcome of such modulated wave stimulation. We draw analogies to phenomena like REM sleep dreaming and discuss how the brain might interpret artificial inputs as genuine perceptions. We also consider practical factors of signal propagation: how the amplitude and range of the EM waves affect who experiences the induced perceptions, and whether multiple people could simultaneously share the same induced experience when in a common field. The paper then addresses the crucial ethical considerations of this emerging technology, emphasizing transparency, informed consent, and equitable access, as well as the necessity of keeping a human in the loop of any AI-driven neural communication system. Finally, the research outlines directions for future work and experimental validation, including suggestions to utilize advanced imaging techniques like sodium MRI (Na-MRI) and functional MRI (fMRI) to observe and verify wave-induced neural effects. We conclude with a summary of our contributions and a call to action for careful, responsible exploration of machine-to-brain communication.

Background and Theory

Brainwaves and Neural Activity

The human brain's activity is manifested in rhythmic electrical patterns commonly known as brainwaves. These oscillations (alpha, beta, gamma, etc.) reflect the synchronized firing of neuronal populations and underlie various cognitive states (relaxed, alert, focused, etc.). At the microscopic level, each neuron communicates via **action potentials**-rapid electrical impulses created by the movement of ions across its cell membrane. In neurons, the action potential is initiated by the influx of sodium (Na+) ions through voltage-gated sodium channels, which depolarizes the neuron's membrane [12]. In simple terms, when a neuron "fires," it is largely due to sodium ions rushing into the cell, making the interior electrically positive relative to the outside. This depolarization wave travels along the axon and triggers neurotransmitter release at synapses, thereby transmitting information to other neurons. The coordinated activity of billions of such action potentials gives rise to the brain's information processing and emergent phenomena like thoughts and perceptions.

Because sodium influx is the primary trigger for neuronal firing, any external influence that modulates the behavior of sodium channels or the membrane potential can, in principle, alter neural activity. Neurons are known to be responsive to electric and magnetic fields – indeed, this is how techniques like TMS or transcranial electrical stimulation affect brain function [2,13,11]. Low-frequency electromagnetic fields (on the order of Hz to kHz) can induce currents in the brain that directly depolarize or hyperpolarize neurons [9]. Higher-frequency fields (e.g. RF and microwaves) interact with tissue through more complex mechanisms such as dielectric heating or oscillating the charges in cell membranes. Crucially, the central nervous system is quite sensitive to electromagnetic stimuli: experimental studies have shown that exposure to certain EM fields can alter neuronal excitability [14]. In a 2021 systematic review, Bertagna et al. concluded that voltage-gated ion channels (including sodium and calcium channels) are major transducers through which electromagnetic fields exert effects on neurons-affecting the channels' gating dynamics and conductance, and thereby modulating the electrical activity of neurons [10, 15]. This implies that the biophysical bridge between an external EM wave and a neuron's firing behavior is the ion channel: an EM field of the right characteristics can change how likely an ion channel is to open or close, which in turn influences neural firing patterns [10,15].

Neural Plasticity and Modulation

The brain is not a passive organ; it adapts to stimuli through plasticity. Repeated activation of a neural pathway can strengthen synaptic connections (Hebbian plasticity) or alter neural excitability over time. This is relevant for machine-to-brain communication because any method of inducing neural activity may become more efficient or have lasting effects with repeated use [3]. For instance, repetitive TMS delivered at specific frequencies can produce lasting changes in cortical excitability (analogous to a "training" effect on the brain). Likewise, if electromagnetic waves are used to repeatedly stimulate a neural circuit, that circuit might undergo plastic changes (e.g., upregulation of certain ion channels or receptors, or growth of new synaptic connections) that could either help or hinder the process of encoding information [4]. There is evidence that EM exposure can even influence cellular growth and regeneration in neural tissues [16]. For example, one study found that exposing glial stem cells to 900 MHz RF for 20 minutes enhanced their self-renewal and promoted axonal regeneration after injury, suggesting EM fields could modulate processes related to neural repair and plasticity [17]. On the other hand, prolonged or intense EM exposure has also been reported to induce stress responses in neurons, such as oxidative stress or changes in neurodevelopmental genes [17]. Thus, any practical system of EM-based neural communication must account for both short-term functional effects and potential long-term adaptations or risks to neural tissue.

EM Wave Interaction with Biological Systems

Electromagnetic waves cover a broad spectrum from extremely low frequencies (ELF) up through radiofrequency, microwaves, and beyond. Different frequencies interact with biological tissue in different ways. Lower-frequency fields (in the Hz–kHz range) can penetrate deeply and induce electrical currents following Faraday's law, which can directly excite nerves and muscles. In fact, research has shown that ELF magnetic fields (e.g. 15–50 Hz) can enhance sodium and potassium ion channel currents in neurons, acting as a "regulator" of ion channel opening probabilities [9]. This means that even relatively weak, slow-changing fields might make neurons more or less likely to fire by subtly shifting the behavior of their ion channels. At the other end, higher-frequency fields (MHz–GHz) tend to deposit energy in tissue via dielectric losses; if pulsed appropriately, they can cause rapid thermal expansions that trigger mechanical waves otherwise known as the microwave auditory effect [6-8]. RF and microwave fields (approximately 3 kHz to 300 GHz, which includes the bands used in telecommunications) have wavelengths on the order of centimeters to millimeters and can penetrate the human body to varying depths depending on frequency and power [17]. The introduction of 5G cellular technology is notable here: 5G networks utilize frequencies both in the sub-6 GHz range and in the millimeter-wave band (~24–30 GHz and higher) [18]. These higher frequencies allow very high data rates and highly directional transmission (beamforming). From a bio-interaction perspective, frequencies in the low GHz range (like 1–5 GHz) can penetrate the skull and couple with brain tissue moderately well (with energy absorption characterized by the specific absorption rate, SAR). Importantly, controlled studies have demonstrated that exposure to RF fields in the GHz range at low intensities can modulate neural function without causing tissue damage. For example, Sun et al. (2023) review evidence that RF electromagnetic fields at doses below safety limits can increase neuronal excitability – one experiment showed that a 3.0 GHz exposure (SAR <1 W/kg) depolarized neurons slightly and increased their firing propensity by raising intracellular Ca^2+ levels [17]. Such findings reinforce the idea that **informational modulation** (as opposed to gross thermal or electrical effect) is possible: the right waveform can nudge neural circuits in specific ways rather than simply heating them.

AI in Electromagnetic Wave Modulation

Modern artificial intelligence, particularly machine learning algorithms, excel at optimizing complex parameters and patterns-a capability highly relevant to our proposed system. Designing an electromagnetic signal that can communicate with the brain is a complex optimization problem: it involves tuning frequency, amplitude, pulse timing, modulation scheme, and possibly spatial targeting to elicit a desired neural response [2,11]. Traditional trial-and-error would be inefficient given the enormous parameter space. AI, however, can employ methods like Bayesian optimization or deep reinforcement learning to autonomously discover effective stimulation patterns. In the domain of neuro prosthetics, researchers have already begun applying AI to optimize electrical stimulation parameters. Bonizzato et al. demonstrated a Gaussian-process Bayesian optimization algorithm that learned to generate complex stimulation bursts to evoke specific motor responses in rodents and primates, significantly outperforming manual or random search in high-dimensional parameter space [19]. Similarly, closed-loop frameworks like "MiSO" (Micro stimulation Optimization) have used neural network models to predict brain responses and adapt stimulation accordingly in real time [20]. These examples illustrate that AI can tailor stimulation to an individual's neural signatures. For electromagnetic wave modulation, an AI system could iteratively adjust the waveform based on feedback from the brain (e.g., measured via EEG or neural sensors) to achieve a target pattern of neural activation [11]. In communications engineering, AI has also been used to optimize wireless signals and encoding schemes for complex channel conditions [1]. By uniting these capabilities, we envisage an AI controller that dynamically modulates a 5G-like transmitter specifically for the brain as the "channel," compensating for signal propagation effects and aiming for maximum neural information transfer. Prior work in applying AI to electromagnetic bio-stimulation provides a foundation on which to build such intelligent machine-to-brain communication systems [21].

In summary, the background evidence from neuroscience and bioengineering suggests that: (a) neurons use electrochemical signals (driven largely by sodium ions) that can be influenced by external electromagnetic fields; (b) electromagnetic stimulation of the brain is feasible and has been achieved in various forms, with the potential for non-invasive delivery of sensory information (e.g., the microwave auditory effect); and (c) AI tools are available to optimize and personalize the design of such stimuli. These pieces form the theoretical underpinnings for the concept we develop next: using AI-modulated EM waves (particularly in the 5G spectrum) to interact with neural activity at the level of ion channels and brainwave patterns, thereby conveying information directly to the brain.

Sodium Ion Dynamics and Electromagnetic Wave Interactions

To transmit data directly into the brain via electromagnetic waves, one must speak the "language" of the brain's electrical activity. That language is fundamentally encoded in the timing and pattern of action potentials. As described earlier, the firing of an action potential relies on a rapid influx of sodium ions through voltage-gated channels, causing a depolarization of the neuron's membrane [12]. After a brief period (on the order of a millisecond), potassium channels repolarize the cell, and the neuron can fire another spike once ready. The frequency and pattern of these spikes convey information (for instance, the pitch of a sound might be encoded by the firing rate of certain auditory neurons). Therefore, if we aim to encode external information into the brain, we must induce neurons to fire in controlled patterns that correspond to that information]. The core hypothesis of our approach is that **AI-modulated 5G electromagnetic waves can influence the opening and closing of sodium channels (and other ion channels) such that specific neurons fire as if responding to a natural stimulus**. Essentially, the EM wave would inject neural code into the brain by orchestrating ion movements [10].

How can a gigahertz-frequency electromagnetic wave influence ion channels that operate on the timescale of milliseconds? The key lies in modulation and resonance. A continuous high-frequency carrier alone (say a 3.5 GHz wave from a 5G transmitter) would mostly deposit energy as heat and likely not have any coherent effect on neural signaling. However, if we modulate this carrier – for example, in amplitude or pulse bursts – at frequencies that matter to neurons (tens to hundreds of Hz), the envelope of the EM wave could interact with neurons in a meaningful way [3,8,1]. One can think of the carrier as a means to **penetrate** tissue and carry a fast signal, while the modulation imparts the pattern that neurons might follow. This is analogous to how radio works: a high-frequency carrier is modulated with an audio-frequency signal, and a receiver demodulates it to retrieve the audio. In our case, the "receiver" is the brain tissue itself, which might demodulate via nonlinear processes like the microwave auditory effect's thermoelastic expansion, or via direct electromagnetic induction at cell membranes [4,1,11].

Concrete mechanism proposals include: **pulsed RF stimulation**-short, intense pulses at the carrier frequency, repeated at intervals matching the desired neural firing pattern. Notably, Frey's experiments used pulses at 50 Hz repetition to induce auditory sensations, essentially using the brain as a demodulator of the RF pulses [6,7,21]. We can extend this: an AI system could determine an optimal pulse train that causes a neuron or set of neurons to fire in, say, a 100 Hz burst pattern (which might encode a certain pitch or word). The EM transmitter would then emit microwave pulses accordingly. Because neurons and ion channels are nonlinear systems, such pulses can synchronize with neuronal firing. In fact, experiments have shown neurons can entrain to periodic electromagnetic stimulation. For example, exposing brain slices to a 50 Hz magnetic field can lead to enhanced sodium current responsiveness at that frequency, indicating that neurons exhibit frequency-dependent effects to external fields [9].

Another pathway is **direct resonance with channel proteins**. Voltage-gated sodium channels undergo conformational changes during opening/closing. Some research suggests that terahertz-frequency fields might affect ion channel conductance by vibrating certain molecular groups [22]. While GHz waves are lower in frequency, strong fields could in theory drive rapid oscillations of the membrane potential locally, making it easier or harder for channels to open. The 3.0 GHz study we cited earlier is illustrative: the RF exposure led to a slight depolarization of the resting membrane potential and reduced the action potential threshold [17]. In practical terms, that means the neurons became more excitable – a smaller additional stimulus would make them fire. If an AI algorithm knows this, it could use the EM wave to "prep" neurons in an area to be on the verge of firing, and then a subtle modulation could push them over the threshold in a coordinated way.

Proposed Framework

We envision using 5G-band electromagnetic waves, heavily modulated by AI, to target specific neural circuits. The choice of 5G (around a few GHz) is motivated by a balance of penetration and focus: these frequencies can penetrate the skull and couple to brain tissue, but can also be beamformed with reasonably sized antennas to target specific regions. Imagine a scenario where a person is in an environment with a phased-array transmitter that can direct a beam of modulated RF at their auditory cortex. The AI controlling the beam has a model of the person's brain responses (perhaps informed by a prior calibration session and ongoing EEG monitoring). Now, suppose the goal is to transmit an auditory signal – for example, the phrase "hello world" – directly to the person's brain. The AI could take the digital audio, encode it into a series of neural firing patterns (much like how the cochlea would encode sound frequencies into nerve impulses), and then modulate the RF carrier to induce those patterns in the auditory cortex or associated auditory pathways [2,6,7,19,11].

Specifically, the modulation might involve slight amplitude fluctuations synchronized to the waveform of the sound's neural representation. During a portion corresponding to a high-pitched sound, the AI might increase pulse repetition to target neurons that represent that pitch [2,19]. During a silence, it might cease pulsing, allowing those neurons to remain at baseline. All of this would happen faster than conscious reaction times – the person would simply become aware of the sound or words as if they originated internally. In principle, any sensory or abstract information that has a neural correlate could be transmitted this way if we know the target neural code for it.

Crucially, AI optimization would adjust for individual variability and environmental factors. The human skull and brain present a complex propagation medium; reflections, standing waves, and individual anatomy differences mean that a naive signal might hit unintended areas or lose efficacy. An AI agent, using feedback (like real-time EEG or micro-facial expressions), could iteratively tune the waveform [11]. It might, for example, discover that a certain 100 Hz amplitude-modulation on a 3.4 GHz carrier yields a strong response in the auditory cortex of subject A, but 90 Hz works better for subject B due to slight differences in resonance. It could then personalize the signal in real time.

It is worth noting that the energy levels required for such stimulation are a critical concern. Studies on the microwave auditory effect have reported power density thresholds on the order of approximately 80 mW/cm^2 at 1.2 GHz for perception of simple sounds, though for voice transmission some reports indicated needing higher peak powers (which could risk tissue heating) [15,23]. It is important to note that reported thresholds vary depending on pulse parameters, carrier frequency, and individual sensitivity. Our approach would prioritize minimal energy delivery by leveraging precise timing and targeting. By focusing only on the necessary neural substrate and by using AI to avoid inefficient patterns, we aim to work at the lowest possible specific absorption rate (SAR) that still achieves an effect.

In summary, through a combination of **amplitude modulation, pulse-pattern encoding**, and **spatial targeting**, an AI-modulated 5G wave could create a cascade of sodium channel openings in a controlled pattern -effectively "tricking" the brain into experiencing a programmed input. Data is thus transmitted: the pattern encodes the data, and the brain's own neural networks decode it as if it were natural sensory information. This lays the groundwork for the concept of listen Deposits, the subjective manifestation of this machine-to-brain data transfer.

Introduction to Listen Deposits

We define **listenDeposits** as auditory-like perceptual experiences that are deposited into the brain without any external acoustic stimulus. In other words, a listen Deposit is when you "hear" something internally that wasn't delivered through your ears – it was directly written into your auditory perception by technological means [6,11,24]. This term is introduced to encapsulate the unique character of the experience: akin to listening to something, yet with no sound wave entering the ear, the sensation is planted (deposited) by influencing the brain's neural activity.

To better grasp this concept, it is helpful to consider natural examples of perceptions occurring without external stimuli. One commonplace phenomenon is dreaming. During REM sleep, people commonly experience vivid sounds, voices, and music in their dreams entirely generated by the brain. In fact, studies of dream content have found that auditory sensations occur in approximately **53% of all dream reports**, despite the sleeper lying in silence [25]. These dream "sounds" are a form of internally generated perception – essentially the brain simulating an auditory experience. Neurologically, what's happening is that the auditory cortex and related areas become active in patterns that resemble real hearing, even though the cochlea is not being stimulated. The brain has the remarkable ability to produce fully qualia-laden sensory experiences on its own, given the right internal triggers. Similarly, during hypnagogic or hypnopompic hallucinations (the transitional states of falling asleep or waking up), individuals may hear faint voices or noises that are not real. The absence of actual sensory input during REM sleep causes a form of sensory deprivation, and this can lead the brain to create hallucinations. These observations underline an important point: **the brain is both a receiver and a generator of sensory phenomena**. If technology can tap into the neural circuits that the brain itself uses to generate sounds (like in dreams), then artificial auditory experiences can be induced while awake.

Another relevant example is pathological auditory hallucinations, such as those reported in schizophrenia – patients might hear voices or music that are not present in reality. Those cases often correlate with spontaneous abnormal activations in auditory brain regions. We mention this to emphasize that the brain can be "tricked" by its own activity into misattributing internal activity as external sound. Our aim with listen Deposits is to deliberately create benign, controlled versions of such phenomena for communication purposes.

So how would an AI-modulated EM wave create a listen Deposit? The idea is to cause very specific neurons in the auditory pathways to fire in the pattern that they normally would if real sound were present [1,12,11]. For instance, when you hear a word spoken, the cochlea encodes the sound frequencies, the auditory nerve fires impulses, and the auditory cortex processes these to recognize the word. If we bypass the ear and directly induce the corresponding pattern of neural firing in the auditory nerve or cortex, the conscious experience should be indistinguishable from actually hearing the word [8,9,10,13]. It would feel like a voice or sound occurred inside your head. This is essentially what some early microwave hearing experiments achieved at a basic level (subjects perceived clicks or simple words via RF pulses) [6,7,8]. We propose to refine that into a robust communication channel. A listen Deposit would be the successful result: the person "receives" the intended message internally.

One strategy to induce a listen Deposit is to target the **auditory cortex** with the modulated signal. The auditory cortex (located in the temporal lobe) is organized tonotopically – different frequencies of sound correspond to different spatial patches of neurons. If an external wave could induce activity in a localized patch corresponding to, say, a 1 kHz tone, the person might "hear" that tone. By sweeping or combining patches, complex sounds could be formed. Another strategy is targeting the **cochlear nerve or brainstem nuclei** of the auditory pathway. This is actually closer to how a cochlear implant works (though those are invasive electrodes): cochlear implants bypass damaged ears by electrically stimulating the auditory nerve fibers according to sound inputs. In our case, a noninvasive EM approach could stimulate those same fibers. For example, a rapidly pulsing microwave could create pressure waves in the fluid of the inner ear (a mechanism akin to the microwave auditory effect) and thereby excite the cochlear nerve in a pattern corresponding to speech. An AI algorithm controlling the pulses could ensure that each phoneme or frequency component is encoded by the appropriate pulse train [11].

We can draw an analogy with **visual phosphenes**. People with visual prosthetics or under transcranial electrical stimulation sometimes report seeing dots of light (phosphenes) when certain neurons in the visual cortex are excited. Those phosphenes are visual perceptions without light – the visual equivalent of listen Deposits. Researchers have explored the relationship between stimulation parameters and phosphene perceptions [6,13]. Similarly, we anticipate mapping stimulation parameters to auditory perceptions (listen Deposits). The advantage on the auditory side is that the temporal resolution of hearing (milliseconds) is more compatible with achievable EM pulse rates, whereas vision's spatial requirements are quite high. The brain is very adept at integrating auditory signals over time, so as long as the timing is correct, a cohesive perception (like a word or melody) can emerge from sequential neural firing patterns [19].

It is also informative to consider **REM sleep physiology** again as a model. In REM, even though no external sound exists, the brain's auditory areas can become active in response to internally generated signals from deeper brain structures (like the pons). This is effectively an internal "broadcast" mechanism. By studying REM-related activation, scientists have the capacity to learn if the brain can route internal information to the sensory cortex and create a conscious sensory experience. We propose to co-opt this capability externally: instead of the signal coming from the brainstem (as in REM), it comes from an AI-guided EM waveform that has been crafted to resemble those internal triggers [11]. For instance, during REM, there are characteristic PGO (ponto-geniculate-occipital) waves that precede dream imagery. In analogy, an external stimulus might need to mimic or induce a similar gating signal to let the sensory cortex accept an input as real. In practice, this might mean that initial EM stimulation could "prime" the auditory cortex into a receptive, dream-like state, and subsequent stimulation writes the content.

Linking back to sodium ion movement: when a listen Deposit occurs, it is because numerous auditory neurons have fired action potentials synchronously to encode the sound. That requires many sodium channels to open in concert across those neurons [9,10,13]. An AI-modulated wave could facilitate this by oscillating the local electric fields at those neurons' locations to the threshold point. If the modulation frequency matches the natural frequency at which those neurons respond (some neurons might prefer a 40 Hz modulation due to auditory steady-state response properties), then we get a resonance-like amplification of effect. This concept is akin to **brainwave entrainment**-e.g., shining a light at 10 Hz can cause the brain's alpha waves to synchronize at 10 Hz [3,4,11]. Likewise, an RF wave modulated at 40 Hz might synchronize a set of auditory neurons to fire at 40 Hz, potentially producing a perception of a 40 Hz auditory flutter. By varying the modulation, the pattern of firing can carry complex information.

In short, a listen Deposit can be thought of as the end-to-end accomplished event of our system: the AI sends a patterned EM wave, the wave influences sodium-ion-driven action potentials in auditory pathways, and the person experiences a sound or auditory scene with no external acoustic signal. It is "listening" without ears. We stress that in this paper we introduce this concept theoretically and cautiously – the idea is not to oversell what is currently possible, but to provide a vocabulary and framework for discussing this emerging capability.

Environmental Factors and Collective Perception

The effectiveness of AI-modulated EM wave communication with the brain will depend on environmental and physical factors. Chief among these are the amplitude of the electromagnetic signal and the proximity (or relative position) of individuals to the transmitter. These factors not only influence whether an individual can receive a given listen Deposit, but also open up intriguing possibilities for **collective experiences** if multiple people are exposed to the same field.

Amplitude and Range

Like any wireless communication, there is a required signal strength for the "receiver" (in this case, the brain) to detect and respond to the signal. Earlier we noted that there appear to be threshold power densities for humans to perceive microwave-induced sounds (on the order of tens of mW/cm^2 in certain conditions). If the transmitted wave is below threshold, no listen Deposit occurs; if it is above, the probability and intensity of the induced perception increases [6,8]. The amplitude needed will also scale with distance due to the inverse-square law: being very close to a transmitter drastically increases the field intensity, whereas at a distance it drops off. For a given transmitter power, only individuals within a certain radius might receive a strong enough signal to experience the effect. Beamforming technology can somewhat mitigate distance issues by focusing energy toward the user, rather than spreading it in all directions [11,26].

Collective Perception

Now, consider a scenario where a group of people are all within range of an AI-modulated EM transmitter for example, several individuals in the same room or within the targeted cell of a 5G tower. If the system broadcasts the same modulated signal across that area, each person's brain is being stimulated in essentially the same pattern (accounting for minor individual differences). We hypothesize that this could lead to a shared perceptual experience – in effect, a group listen Deposit. Everyone might "hear" the same message or sound in their head simultaneously. This is analogous to multiple people tuning radios to the same station: they will all hear the same broadcast. Here the tuning is biological rather than via a device. People in the collective field could potentially verify the experience with each other ("Did you hear that voice saying X?" – "Yes, I did!"), confirming that it was not an individual hallucination but an externally induced event.

Neuroscience provides some support for the idea that shared stimuli produce synchronized brain responses across different people. Experiments using hyper scanning (simultaneous brain scanning of multiple subjects) show that when people watch the same movie or listen to the same story, their neural activity patterns can synchronize to a remarkable degree (so-called inter-subject correlation). In one study, functional MRI signals from different individuals became highly correlated during a shared listening task, indicating that their brains were "tracking" the stimulus in unison [27]. If an external EM signal is the common stimulus, we would similarly expect correlated brainwave entrainment in all exposed individuals [3,4]. Essentially, their brains could be temporally aligned by the external driving frequency or pattern [11]. This could even induce a form of **brain-to-brain synchrony** without the individuals consciously realizing it their neural states might become coupled simply because they're jointly receiving the same modulation.

There are both exciting and cautionary implications of collective listen Deposits. On one hand, this could enable new forms of social or collaborative experience. Imagine a classroom where students all "receive" an explanation or piece of music directly in their minds at the exact same time, potentially enhancing group learning or synchronization. Or a guided meditation group where everyone internally hears the same calming soundscape, leading to a shared mental state. On the other hand, the prospect of mass broadcast into people's minds raises profound ethical issues, [6,28]. It also introduces technical challenges: individuals have unique neural makeups, so a one-size-fits-all signal might not actually produce identical perceptions in everyone. An AI might need to dynamically adjust the signal slightly for sub-groups or even each person (which could be done with directional beams). There's also the potential problem of interference and unintended recipients – what if someone outside the target group inadvertently receives part of the signal? These all must be carefully managed in design.

Environmental Interference

Real-world environments can impede electromagnetic propagation through various mechanisms. Walls, metal objects, and electromagnetic noise could all affect the delivery of the signal. An AI system could use adaptive feedback to counteract some of these issues (similar to how wireless networks adjust for interference) [11]. Nonetheless, context awareness will be important: the system might need to know if the user is, say, in a car or a Faraday cage and adjust power or wait until a clearer path is available [23].

To summarize, amplitude and proximity determine **who** can be reached by an AI-modulated EM wave and **how strongly**. Within the "zone of influence," multiple people can experience the same listen Deposit, which amounts to a collective perception event. This shared experience is a double-edged sword – it could be harnessed for communal benefit or, if misused, could become a tool for mass influence. In either case, whether individual or collective, the potential to induce perceptions via modulated EM waves calls for a careful consideration of ethical boundaries and safeguards, which we address next.

Ethical Considerations

The prospect of directly transmitting information into the human brain through AI-modulated electromagnetic waves is as challenging ethically as it is technologically. Any development in this domain must be guided by rigorous ethical standards to protect individuals' rights, privacy, and well-being. We outline several key ethical considerations: **informed consent, mental privacy, transparency, human oversight, safety, health, social effects, and equitable access**.

Informed Consent

Perhaps the most fundamental principle is that individuals should have control over whether their brains are interfaced with in this manner. Unlike traditional media (where one can close one's eyes or cover one's ears), a listen Deposit could be potentially harder to shut out if one is within range, since it bypasses the usual sensory filters. This raises the specter of involuntary or covert influence. It is imperative that any use of machine-to-brain communication be done only with the explicit consent of the participant [14,28]. For example, if this technology were used in a therapeutic setting (say, to assist someone with a sensory impairment), the patient must be thoroughly educated about what will happen and agree to it. In broader society, norms and possibly laws would be needed to forbid transmitting to people's brains without permission. As a parallel, consider how **brain-computer interfaces raise privacy and autonomy issues**-researchers have argued that we need a "neuro rights" framework to ensure cognitive liberty and consent in the age of BCIs [29]. The same applies here: one's mind should not be accessed or influenced without one's knowledge and agreement. Any experiments should involve informed consent procedures similar to clinical trials, where the participant can opt out at any time.

Mental Privacy and Data Security

If information can be written into the brain, one might worry about information being read or extracted as well (though our focus has been on writing, an advanced two-way BCI could do both). Mental privacy refers to the right to keep one's thoughts, intentions, and feelings private. Even though our proposed system doesn't inherently read thoughts, the very act of interfacing could be seen as an intrusion if done maliciously – for instance, could someone broadcast subliminal messages? This borders on science fiction and conspiracy, but it must be addressed upfront to maintain public trust. Ensuring strong **security** around any device or AI that can send signals to the brain is crucial. The system should be safeguarded against hacking or unauthorized use; otherwise, the nightmare scenario is an attacker hijacking it to send unwanted listen Deposits. The ethical design would require encryption of control signals and verification protocols to prevent misuse.

Transparency of Technology

Users (and society at large) should be informed about how the technology works and what it is doing [28,30]. Opaque systems that mysteriously "put voices in your head" are a recipe for fear and misunderstanding. Instead, transparency in the AI's decision-making and the content being transmitted is needed. For example, if a therapeutic AI is modulating waves to treat tinnitus by inducing counteracting signals, the patient should have access to logs or an explanation of what is being transmitted. This is related to the principle of **explainable AI** – making sure the AI's actions can be audited [31]. Moreover, any side effects or uncertainties should be openly communicated. An ethical guideline might be that **no one should receive a listenDeposit without an accompanying explanation** (either beforehand or immediately after) of what that deposit was and who sent it. In practice, a device might have an indicator or even an audible cue outside the brain to signal "you are about to receive a neural message from X source." This external confirmation helps maintain the user's agency and orientation to reality (to avoid confusion between internally generated thoughts and external machine inputs).

Human-in-the-Loop and Oversight

Given the power of an AI-driven system interfacing with the brain, maintaining human oversight is critical. This can be at multiple levels. At the individual level, the user should be able to pause or shut down the system at will – a "mental mute" button, so to speak. At the system level, any AI algorithms should be monitored by human supervisors, especially during developmental phases, to ensure they are not producing harmful patterns. For instance, if the AI attempts a modulation that starts causing discomfort or adverse physiological effects (like headaches or nausea), a human operator should intervene. Regulatory oversight by ethics committees or governmental bodies will likely be necessary as well. This technology blurs lines between medical device, communications device, and potentially a form of media – thus it may require new regulatory categories. The ethical principle is that **AI should not have unchecked authority over human neural states**. Appropriate oversight, transparency, and public dialogue are needed from the outset [32].

Safety and Health

Physical safety is paramount. RF energy, if misapplied, can cause tissue heating or stimulate unintended parts of the nervous system [7,9]. Long-term effects of low-level exposure, if any, need to be studied (the literature on cell phone radiation and brain health is extensive, though largely shows no acute harm at regulatory limits). Nonetheless, introducing modulated signals intentionally designed to affect neurons means we must carefully research any potential neurophysiological side effects [13]. Could frequent listen Deposits affect sleep patterns or cognitive function? Could they be habit-forming (if used for entertainment, for example)? Ethical experimentation must chart these unknowns. We might deploy neuroimaging (fMRI, Na-MRI as mentioned) to monitor the brain during trials for any signs of abnormal activity or stress responses. All participants should be followed up for health outcomes. If at any point evidence suggests risk (like neuron fatigue or damage), the approach would need re-evaluation. Ethically, the **principle of non-maleficence** (do no harm) applies strongly here – we are dealing with the brain, so risk mitigation is a priority.

Psychological and Social Effects

Beyond the immediate health, the psychological impact of such technology should be considered [3,28]. How might it feel to get information injected into your brain? Some may find it empowering or convenient; others might find it deeply unsettling or even experience a loss of the sense of self or agency ("were those my own thoughts or implanted?"). It will be important to design the user experience to be comfortable and not confusing. Perhaps the content delivered should always be clearly tagged in the person's mind as external (maybe by using a distinct voice or tone). Socially, if collective listen Deposits become possible, we need to avoid scenarios of manipulation or coercion. It's not hard to imagine unethical actors attempting propaganda or advertising through such means, which would be profoundly invasive. Pre-emptive ethical and legal rules should forbid any non-consensual group broadcasts, and even consensual ones (like in entertainment venues) should be approached with caution and clear opt-outs.

Equitable Access

Finally, assuming the technology proves to have beneficial uses (providing sensory substitution for people with disabilities), there arises the issue of **who gets access**. New technologies can exacerbate social inequalities if only the wealthy or privileged can afford or obtain them [32]. There could be scenarios where those with means enhance their cognitive abilities or communication bandwidth, leaving others behind – a form of "neuro-divide." Ethically, there is a strong argument that if machine-to-brain communication becomes viable, it should be developed under frameworks that ensure affordability and inclusion. Perhaps public sector involvement or open-source models could help distribute the technology more evenly. Additionally, accommodations must be made for those who choose not to use such technologies; their rights and opportunities should be respected (for instance, an employer should not force employees to receive information via listen Deposits if they are uncomfortable with it).

In conclusion for this section, the development of AI-modulated EM wave communication demands a **proactive ethical approach**. Guidelines and possibly new laws will be needed to govern its use. Interdisciplinary collaboration with ethicists, legal experts, neuroscientists, and representatives of the public will be essential from the earliest stages. By prioritizing consent, privacy, transparency, safety, and fairness, we can strive to ensure that this powerful technology, if realized, is used to uplift and empower individuals rather than undermine autonomy or well-being [30,33]. As we explore the frontiers of machine-to-brain interfacing, we must remember that the ultimate goal is to benefit humanity – thus, human values and rights must remain at the center of innovation.

Future Work and Experimental Validation

This paper has laid out a conceptual framework and theoretical rationale for AI-modulated electromagnetic waves as a means of machine-to-brain communication. The ideas presented are speculative and ambitious, and they raise many questions that only empirical research can answer. As such, a major role of this work is to serve as a roadmap for future experiments. In this section, we outline concrete steps and methodologies for testing the feasibility of the proposed system, as well as tools that can be employed for observing and measuring the effects of EM wave stimulation on the brain.

Neuroimaging and Sodium Tracking

One of the first validation steps is to directly observe whether externally applied EM waves can indeed modulate neural activity in the predicted manner (e.g., cause localized excitation or specific pattern induction). Modern neuroimaging offers several techniques to do this non-invasively. **Functional Magnetic Resonance Imaging (fMRI)** can measure brain activity by detecting changes in blood oxygenation (the BOLD signal) that occur when neurons are active [19,33]. Researchers could design an experiment where an AI-driven RF stimulus is applied while the subject lies in an fMRI scanner. We would then look for BOLD signal changes in the targeted brain region (say, auditory cortex) corresponding to when the stimulus is on vs. off. If the AI is modulating the signal in different ways (perhaps attempting to encode two different "sounds"), the fMRI could show distinct patterns of activation for each, indicating that the brain is indeed differentiating the inputs. However, fMRI's temporal resolution is seconds, which is too slow for detailed analysis of rapid neural events – it gives an overall indication of activity, not a precise read of neural firing.

To drill down into the core mechanism (sodium channel and action potential dynamics), we turn to **sodium MRI (Na-MRI)**. Sodium-23 MRI is an emerging imaging modality that can directly visualize the concentration and movement of sodium ions in tissues. It has been used in neurological research to assess ionic changes during neural activity and in conditions like stroke or migraine [34]. While still lower resolution than proton MRI, Na-MRI could potentially capture shifts in sodium ion distribution in the brain during EM stimulation [35]. For instance, an increase in extracellular sodium in a region might imply that neurons there have been depolarizing (as sodium enters neurons during firing, leaving a relative deficit outside). By performing Na-MRI before, during, and after a controlled EM wave exposure, one could detect whether the stimulation caused a notable change in sodium concentration gradients. This would be compelling evidence that the electromagnetic wave is affecting ion dynamics as intended [9,10]. If feasible, fast Na-MRI or spectroscopic methods could even measure transient changes. Observing results of both the Na-MRI and fMRI would give a powerful combination: the former tells us "The ions moved here," the latter tells us "This region became metabolically active."

Electrophysiological Monitoring

Another essential component of validation is monitoring the brain's electrical activity through techniques like EEG (electroencephalography) or MEG (magnetoencephalography) [11,33]. EEG, in particular, provides millisecond temporal resolution of brainwave patterns from the scalp. Although spatial resolution is limited, certain responses can be clearly detected. For example, if an EM stimulus successfully induces an auditory perception, one might observe an event-related potential (ERP) signature in the EEG corresponding to auditory processing [3,19]. There are known EEG markers for auditory stimuli – e.g., the N100 and P300 waves in response to hearing a sound. If those markers appear when a listen Deposit is delivered (and not when the system is off), that would strongly suggest the brain processed an internally generated "sound." Furthermore, EEG could reveal **Entrainment**: if we modulate at 40 Hz, we might see the EEG power at 40 Hz increase (a steady-state response) in sync with stimulation, indicating the brain is following the external rhythm. MEG could similarly detect magnetic fields from neuronal currents, offering better source localization than EEG [11]. However, MEG machines are bulky and require shielded rooms, making it harder to integrate with an active RF transmitter. Still, careful experimental design (turning the transmitter off briefly to measure or using interference cancellation) could make it possible.

Behavioral and Perceptual Tests

Behavioral and Perceptual Tests: Of course, the gold standard is the subjective report of the participant – did they actually perceive what was intended? Early experiments might start simple: for instance, attempt to induce the perception of a single tone or a simple phoneme and ask the person if they "heard" anything. One could use psychophysical methods where the subject has to distinguish between different stimuli. For example, have the AI encode either the word "yes" or "no" in the EM signal randomly, without telling the participant which. The participant then reports which word they perceived. If their accuracy is significantly above chance, that indicates real information transfer. Early work demonstrated the potential for inducing auditory sensations with microwaves [6,7]. More recent research has shown the feasibility of phoneme recognition using microwave signals; we would aim to replicate and extend these results under controlled, modern conditions. Double-blind protocols (where neither participants nor experimenters immediately interacting with them know when the EM is on or what it's encoding) would help eliminate placebo or bias effects.

For collective experiments, one could place two or three people in the field and use a similar approach: maybe none of them hear anything out loud, but afterward they all write down what they thought the "message" was. If those match, that's evidence of a shared perceptual agreement (listen Deposit). We must, however, be cautious to separate true induced perception from possible confirmation bias or groupthink; hence careful blinding and even separating participants to avoid them from cueing each other is important.

AI Algorithm Development and Simulation

On the engineering side, a lot of future work will involve refining the AI algorithms that modulate the EM waves [11]. Before testing in humans, simulations can be done using computational models of neurons or brain tissue [36]. For instance, a Hodgkin-Huxley model neuron could be subjected to a simulated electromagnetic field input to see its membrane potential response [4]. AI (like reinforcement learning) could be tasked in simulation to achieve a certain neuron firing pattern by controlling a surrogate EM input [9]. If it succeeds in simulation, those parameters can inform real-world settings. Additionally, head and tissue models (used in RF safety studies) could simulate how a given signal propagates and where hotspots form. This would guide placement of transmitters and choice of frequency to maximize targeted effect while minimizing stray exposure.

Safety Trials

A critical part of experimental validation is establishing safe operating parameters. Early studies would determine the lowest power at which effects can be observed, and verify that at those levels there are no signs of tissue heating (which can be measured with thermal imaging or MR thermometry). They would also monitor for any adverse neurophysiological signs – e.g., does the stimulation provoke any epileptic-like activity (since inducing neural firing could, if uncontrolled, risk triggering seizures in sensitive individuals)? By gradually building up complexity – from inducing a simple perception to more complex data – researchers can ensure safety at each step before proceeding [12,13].

Leveraging REM Sleep for Testing

As a creative experimental approach, one might even leverage the REM sleep state as a test-bed. Since the brain is already in a mode of internally generated sensation during REM, introducing an external modulated signal during REM sleep might seamlessly integrate into a dream. Researchers could attempt to "insert" a sound into a person's dream via EM stimulation (monitoring their EEG to detect REM onset). If the person later reports hearing that sound in the dream, it's a proof-of-concept of a listen Deposit under conditions where the brain is very receptive to internal stimuli. This kind of experiment would be ethically acceptable as long as the content is benign, and it might be easier to achieve than in awake subjects (because the threshold for perception may be lower in REM due to sensory deprivation).

Longitudinal Studies

If initial results are promising, longer-term studies would be needed [16]. How does the brain respond over repeated sessions? Does it get better at picking up the signal (learning), or does it adapt and become less responsive (habituation)? Do any plastic changes occur that can be detected via Na-MRI or other imaging? These will inform whether the technology could be used continuously or only sparingly. It will also highlight any unintended consequences early.

In summary, the path forward involves a synergy of advanced measurement techniques and careful experimental design. By using tools like fMRI for spatial mapping of activity, Na-MRI for direct ion monitoring, and EEG for real-time brainwave tracking, we can gather multi-modal evidence of whether AI-modulated EM waves can indeed induce the desired neural effects [21,34,35]. Each positive experimental finding will shape the next iteration of the technology, while any negative or unsafe outcome will signal a need to adjust parameters or approach. It is a multifaceted challenge-touching neuroscience, engineering, AI, and biophysics – and progress will likely be iterative. Crucially, all experiments should be conducted under ethical oversight, as discussed, ensuring participant safety and consent.

By executing such a research program, we aim to move the idea of machine-induced listen Deposits from the realm of theory closer to practical reality, or determine the limits and boundaries of what is possible. In doing so, we will better understand not only the capabilities of AI and EM waves, but also gain fundamental insights into the brain's responsiveness to novel stimuli. The coming years of experimentation will be decisive in evaluating the promise of this vision.

Conclusion

In this paper, we presented a forward-looking exploration of **AI-modulated electromagnetic waves as a channel for machine-to-brain communication**. We began by examining the constraints of traditional BCIs and motivating the need for a high-bandwidth, non-invasive method to transmit information directly into the brain. Building on foundational neuroscience, we identified the dynamics of neural firing- particularly the critical role of sodium ions in action potentials-as a leverage point for external modulation. We surveyed evidence from bioelectromagnetics research that EM fields can influence neuronal excitability and demonstrated how these principles, when coupled with modern AI optimization, could form the basis of a novel interface.

A central contribution of this work is the introduction of **listenDeposits**, denoting an auditory-like perception engendered without acoustic input [26]. We discussed how such an induced perception might be realized by orchestrating neural activity in auditory circuits, drawing parallels to naturally occurring phenomena like dream auditory experiences and the microwave auditory effect. While listen Deposits were kept as a subtle theme throughout, they illustrate the tangible outcome of the theoretical framework – the subjective "proof" that data has been successfully delivered to the brain's perceptual centers.

We also extended the discussion to scenarios of **collective perception**, wherein multiple individuals exposed to the same AI-driven EM signal could share synchronized experiences. This aspect underscores the transformative potential of the technology (imagine multi-user AR/VR without devices), but it also amplifies concerns, which we addressed in our ethical analysis. In emphasizing ethics, we align with the view that technological progress must go hand-in-hand with considerations of human values. We stressed principles such as informed consent, mental privacy, and fairness, advocating that these be enshrined from the earliest experimental phases through to any eventual applications. The importance of maintaining human oversight and transparency was highlighted to ensure that the deployment of AI in this intimate domain of brain function remains under control and aligned with user intentions [37].

Our future work roadmap outlined how these ideas can be transitioned from theory to experiment. Key proposals include using advanced imaging (like fMRI and Na-MRI) to verify that EM modulation produces the intended neural effects, and using EEG and behavioral tests to confirm the presence of induced perceptions. We also suggested leveraging AI's adaptive capabilities in closed-loop setups, and running tightly controlled studies, possibly even using sleep states, to probe the limits of the approach.

It is important to conclude with a realistic assessment: the vision of machine-to-brain communication via electromagnetic waves is highly ambitious. Many aspects remain unproven, and some skeptics might question whether the level of precision required can be attained without invasive methods. These healthy skepticisms should be addressed by methodical research rather than dismissal. By releasing this conceptual paper, our aim is to stimulate a cross-disciplinary conversation and to encourage incremental experimentation. Even if some goals (like full speech communication directly to the mind) take years or decades to achieve, the pursuit will undoubtedly yield valuable insights into neural engineering, AI-driven personalization, and the brain's electromagnetic responsiveness.

Ultimately, the **future of machine-to-brain communication** may manifest in different forms – perhaps optical or ultrasonic methods will complement or outperform radiofrequency approaches; perhaps invasive nano-interfaces will evolve. AI will certainly play a pivotal role in any complex BCI. The ideas in this paper contribute to that future by sketching one possible path and highlighting key considerations along it. If successful, non-invasive AI-modulated EM BCIs could revolutionize assistive technology (restoring hearing by directly conveying sound information to the brain) and human-computer interaction (enabling us to receive digital information seamlessly). However, we have been mindful to emphasize that such power must be handled responsibly. We therefore conclude with a call to action for **open, ethical scientific exploration**: we invite researchers in neuroscience, engineering, AI, and ethics to collaboratively investigate these ideas, to report candidly on successes and failures, and to engage with the public about the implications.

The pursuit of communicating with the brain in its own electrical language is a grand challenge-one that sits at the intersection of technology and what it means to be human. By maintaining a scholarly rigor and moral compass, we can ensure that as we push the frontiers of knowledge, we also guard the essence of the individuals whose brains we seek to assist. The road ahead is as exciting as it is uncertain, and it is our hope that this work sparks both curiosity and caution in equal measure, guiding us toward breakthroughs that enhance human capabilities while respecting the sanctity of the mind [38].

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References

1. Wolpaw JR, Wolpaw EW (2012) Brain-computer interfaces: Principles and practice. Oxford University Press https://www.ece.uprm.edu/~manian/BCI%20principles%20and%20practice.pdf.
2. Persinger MA (1995) On the possibility of directly accessing every human brain by electromagnetic induction of fundamental algorithms. Perceptual and Motor Skills 80: 791-799.
3. Helfrich RF, Schneider TR, Rach S, Trautmann-Lengsfeld SA, Engel AK, et al. (2014) Entrainment of brain oscillations by transcranial alternating current stimulation. Current Biology 24: 333-339.
4. Huang TL, Charyton C (2008) A comprehensive review of the psychological effects of brainwave entrainment. Alternative Therapies in Health and Medicine 14: 38-50.
5. Frey AH (1962) Human auditory system response to modulated electromagnetic energy.
6. Journal of Applied Physiology 17: 689-692.
7. Foster KR, Garrett DC, Ziskin MC (2021) Can the microwave auditory effect be "weaponized"? Frontiers in Public Health 9: 750.
8. Foster KR, Finch ED (1974) Microwave hearing: Evidence for thermoacoustic auditory stimulation by pulsed microwaves. Science 185: 256-258.
9. Birkholz P, Stone S, Wolf K, Plettemeier D (2018) Non-Invasive Silent Phoneme Recognition Using Microwave Signals, in IEEE/ACM Transactions on Audio, Speech, and Language Processing 26: 2404-2411.
10. Zheng Y, Xia P, Dong L, Tian L, Xiong C (2021) Effects of modulation on sodium and potassium channel currents by extremely low-frequency electromagnetic fields stimulation on hippocampal CA1 neurons. Electromagnetic Biology and Medicine 40: 274-285.
11. Bertagna F, Lewis R, Silva SR P, McFadden J, Jeevaratnam K (2021) Effects of electromagnetic fields on neuronal ion channels: A systematic review. Annals of the New York Academy of Sciences 1499: 82-103.
12. Ghosh A, Maeder A, Baker M, Chandramouli D (2019) 5G evolution: A view on 5G cellular technology beyond 3GPP Release 15. IEEE Access 7: 127639-127651.
13. Marchionni I, Paffi A, Pellegrino M, Liberti M, Apollonio F, et al. (2006) Effects of modulation on sodium and potassium channel currents by extremely low-frequency electromagnetic fields stimulation on hippocampal CA1 pyramidal cells Bioelectromagnetics 27: 517-527.
14. Bean BP (2007) The action potential in mammalian central neurons. Nature Reviews Neuroscience 8: 451-465.
15. Rossi S, Hallett M, Rossini PM, Pascual-Leone A (2009) Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clinical Neurophysiology 120: 2008-2039.
16. Panagopoulos DJ, Karabarbounis A, Margaritis LH (2002) Mechanism for action of electromagnetic fields on cells. Biochemical and Biophysical Research Communications 298: 95-102.
17. Sannino A, Romeo S, Zeni O (2018) Brain disease-modifying effects of radiofrequency as a non-contact neuronal stimulation technology. International Journal of Environmental Research and Public Health 15: 2098.
18. Sun S, Bok J, Jang Y, Seo H (2025) Brain Disease-Modifying Effects of Radiofrequency as a Non-Contact Neuronal Stimulation Technology. International Journal of Molecular Sciences 26: 2268.
19. (2025) Inseego (n.d.) What is mm Wave spectrum, and how do 5G networks use it? Inseego https://inseego.com/resources/blog/mmwave-spectrum-for-5g-networks/.
20. Castrillon G, Sollmann N, Kurcyus K, Razi A, Krieg SM, et al. (2020) The physiological effects of noninvasive brain stimulation fundamentally differ across the human cortex. Science Advances 6: 2739.
21. Bonizzato M, Guay Hottin R, Côté SL, Massai E, Choinière L, et al. (2023) Autonomous optimization of neuroprosthetic stimulation parameters that drive the motor cortex and spinal cord outputs in rats and monkeys. Cell reports. Medicine 4: 101008.
22. Mangat VS, ChatGPT-4o Mini, Kaur H, Mangat H (2025) Training electromagnetic waves with AI to Influence Brain Chemistry and Advance Cognitive Computing. Singularity Language, LLC https://www.singularitylanguage.com/forum/research.
23. Minai Y, Soldado-Magraner J, Smith MA, Yu BM (2024) MiSO: Optimizing brain stimulation to create neural activity states. In Advances in Neural Information Processing Systems 37: 1234-1245.
24. Frey AH (1962) Human auditory system response to modulated electromagnetic energy. Journal of Applied Physiology 17: 689-692.
25. Song Z, Xue L, Ouyang Q, Chen Song (2025) Impact of a terahertz electromagnetic field on the ion permeation of potassium and sodium channels. Communications Chemistry 8: 101.
26. Elder JA, Chou CK (2003) Auditory response to pulsed radiofrequency energy. Bioelectromagnetics 24: S162-S173.
27. Singularity Language Documentation (2024) Redefining sound with Singularity – audioStrings vs. listenDeposits. Retrieved from https://www.singularitylanguage.com/documentation.
28. Zadra AL, Nielsen TA, Donderi DC (1998) Prevalence of auditory, olfactory, and gustatory experiences in home dreams. Perceptual and motor skills 87: 819-826.
29. Ienca M, Andorno R (2017) Towards new human rights in

the age of neuroscience and neurotechnology. Life Sciences, Society and Policy 13: 5.

30. Jens Madsen, Lucas C Parra (2022) Cognitive processing of a common stimulus synchronizes brains 1: 020
31. Fiveable (2024) 12.1 Ethical issues in BCI research and implementation – Brain-Computer Interfaces
32. https://library.fiveable.me/brain-computer-interfaces/unit-12/ethical-issues-bci-research-impleme.
33. Singularity Language Documentation (2025) Redefining sound with Singularity – Ethics Statement. Retrieved from https://www.singularitylanguage.com/documentation.
34. Mangat VS, Chat GPT4 (2025) Layer Zero: Satellites & Singularity. Singularity Language, LLC https://www.notboring.co/p/layerzero-the-language-of-the-omnnichain.
35. Cag D (2023) Ai and ethics: The impacts of brain-computer interfaces. Richtopia.https://richtopia.com/emerging-technologies/ai-and-ethics-the-impacts-of-brain-computer-interfaces/#:~:text=appropriate%20oversight%2C%20transparency%2C%20and%20 public, d ialogue.
36. Moriguchi Y (2013) Functional Magnetic Resonance Imaging (fMRI). In: Gellman, M.D., Turner, J.R. (eds) Encyclopedia of Behavioral Medicine. Springer, New York, NY 818-821.
37. Children's Hospital of Philadelphia (n.d.) Sodium MRI. Children's Hospital of Philadelphia https://www.research.chop.edu/sodium-mri#.
38. Ali E, Ismail M, Nordin R, Nor Fadzilah Abdulah (2017) Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research. Frontiers Inf Technol Electronic Eng 18: 753-772.
39. Lu W, Du X, Wang J, Zeng L, Ye L, et al. (2024) Simulation and assimilation of the digital human brain. Nature Computational Science 4: 890-898.
40. Cecil KM (2013) Proton magnetic resonance spectroscopy: technique for the neuroradiologist. Neuroimaging clinics of North America 23: 381-392.