ORIGINAL ARTICLE

MindNet: the best network is human

Welcome to the Neural Internet — a closed-loop, multimodal architecture that integrates telecommunications, rt-fMRI, HP-^{13}C MRI, RF, Pyneal, TCP/IP, and artificial intelligence to acquire, encode, transmit, modulate, and synchronize neural states between individuals.

Juliana Lourenço Lopes Demasi[1], *MEDICAL STUDENT (3rd semester)*

[1]National Ecological University, Santa Cruz de la Sierra.

ORCID: 0009-0005-7192-0458. LATTES:8792875021530351

E-mail: julianademasi@gmail.com

About the article:

MindNet is proposed as a multimodal, closed-loop neural communication architecture designed for the acquisition, processing, modulation, transmission, and synchronization of neural states between individuals. The proposed architecture integrates real-time functional magnetic resonance imaging (rt-fMRI), metabolic magnetic resonance imaging with hyperpolarized carbon-13 (HP-13C MRI), RF, Pyneal, TCP/IP, and artificial intelligence to create a computational representation of neural states and transmit this information digitally from the sender to the receiver.

The proposal is based on advances already demonstrated in different fields, and the central hypothesis of *MindNet* is that these components, currently distributed among different lines of research, can be integrated into a computational architecture in which each cycle of acquisition, transmission, reception, and synchronization produces new information used to determine the next cycle.

Keywords: *MindNet; brain-to-brain;* fMRI; rt-fMRI; HP-1^{3}C MRI; artificial intelligence; *neural decoding; hyperalignment; hyperscanning; neurofeedback;* neural communication; *closed-loop system.*

SUMMARY

O presente estudo explica a solução proposta chamada MindNet como uma arquitetura multimodal de telecomunicações neurodigitais em circuito fechado, destinada à aquisição, processamento, representação, transmissão e sincronização de informação derivada de estados neurais entre indivíduos. A proposta integra princípios de neurociência, inteligência artificial, teoria da informação e engenharia de telecomunicações, considerando a rt-fMRI e RF como mecanismo de aquisição funcional, e a HP-^{13}C MRI como modalidade complementar de caracterização metabólica obtida em tempo real, e algoritmos computacionais para redução de ruído, extração de características, neural decoding e construção de representações digitais dos estados cerebrais. Após a conversão neural-digital, essas representações podem ser codificadas, packetizadas e transmitidas por redes convencionais de telecomunicações, incluindo infraestrutura baseada em TCP/IP, eliminando a necessidade de propagação direta de campos cerebrais ou de MRI entre indivíduos geograficamente separados. Métodos de alinhamento interindividual, como hyperalignment, são considerados como possíveis mecanismos para estabelecer espaços representacionais compartilhados e permitir a comparação de informação entre cérebros com organizações funcionais individuais.

O estudo também propõe implementação da MindNet a partir de precedentes experimentais ja existentes acerca de seus principais componentes funcionais, incluindo processamento de fMRI em tempo real, neural decoding não invasivo, comunicação cérebro–cérebro, Brainets, transmissão digital de informação derivada de atividade cerebral (DICOM), hyperscanning e alinhamento de representações neurais entre indivíduos. A arquitetura proposta se torna bidirecional ao incorporar a reacquisição do estado cerebral do receptor e sua utilização concomitantemente durante o pulso de MRI/RF. Após a recepção da informação, a resposta neural é medida, representada e comparada ao estado de referência do emissor, permitindo calcular parâmetros que melhor traduzam seus estados neurais. Dessa forma, o estudo explica a solução e discute a implementabilidade técnica da arquitetura proposta pela Mindnet propondo que variáveis como fidelidade, latência end-to-end, neural bandwidth, taxa de erro e closed-loop gain sejam utilizadas para caracterizar o funcionamento, a eficiência e a progressiva otimização da MindNet como sistema de telecomunicações neurodigitais.

ABSTRACT

The present study describes the proposed solution, called MindNet, as a multimodal closed-loop neurodigital telecommunications architecture designed for the acquisition, processing, representation, transmission, and synchronization of information derived from neural states between individuals. The proposed architecture integrates principles of neuroscience, artificial intelligence, information theory, and telecommunications engineering, considering real-time functional MRI (rt-fMRI) and radiofrequency (RF) as mechanisms for functional acquisition, hyperpolarized carbon-13 magnetic resonance imaging (HP-^{13}C MRI) as a complementary modality for real-time metabolic characterization, and computational algorithms for noise reduction, feature extraction, neural decoding, and the construction of digital representations of brain states.
Following neural-to-digital conversion, these representations can be encoded, packetized, and transmitted through conventional telecommunications networks, including TCP/IP-based infrastructure, eliminating the need for the direct propagation of brain-generated or MRI fields between geographically separated individuals. Interindividual alignment methods, such as hyperalignment, are considered as potential mechanisms for establishing shared representational spaces and enabling the comparison of information across brains with individual functional organizations.

The study also proposes the implementation of MindNet based on existing precedents for its main functional components, including real-time fMRI processing, non-invasive neural decoding, brain-to-brain communication, Brainets, digital transmission of information derived from brain activity, including through DICOM-based imaging infrastructure, hyperscanning, and the alignment of neural representations across individuals. The proposed architecture becomes bidirectional by incorporating reacquisition of the receiver's brain state and its concomitant use during the MRI/RF pulse sequence. Following information reception, the neural response is measured, represented, and compared with the sender's reference state, enabling the calculation of parameters that more accurately characterize their respective neural states. In this way, the study explains the proposed solution and discusses the technical implementability of the MindNet architecture, proposing that variables such as fidelity, end-to-end latency, neural bandwidth, error rate, and closed-loop gain be used as quantitative metrics to characterize system operation, evaluate efficiency, and guide the progressive optimization of MindNet as a neurodigital telecommunications system.

AUTHOR PROFILE



Ju Lourenço is a third-year medical student and is studying *Fundamentals of Neuroscience* through the HarvardX/edX program. Her professional experience includes working in telecommunications and advanced internet products, participating in the creation, implementation, promotion, and discontinuation of products, as well as the development of value-added services and digital initiatives. Her work involved not only commercial and marketing aspects but also interaction with multidisciplinary teams and participation in decision-making regarding the technical and strategic implementation of advanced internet and telecommunications products. Her professional experience also includes working in *Business Intelligence,* engineering, and IT companies.

Her academic background reflects the same interdisciplinary characteristic mentioned earlier and includes an MBA in Finance from IBMEC (Brazilian Institute of Capital Markets), an MBA in Marketing from FGV (Getulio Vargas Foundation), a Master's degree in Mass Communication from PUC-Rio (Pontifical Catholic University of Rio de Janeiro), and a degree in Advertising and Public Relations. Ju was a FAPERJ scholarship recipient, and her research focused on classification.

This combination of communication, market analysis, finance, technology, and research has contributed to a professional trajectory marked by the convergence of technical knowledge, human behavior, and new product development. Ju is also a journalist by profession and an inventor by passion.

She lived for 12 years in the San Francisco Bay Area, in the technological ecosystem associated with Silicon Valley, an experience that reinforced her affinity with the culture of innovation and technology. At the same time, she maintains an artistic and literary career, with artistic and academic works published at different times. This coexistence between technology and creation ended up producing a definition that well summarizes his trajectory: "too techie to be just an artist and too much of an artist to be just a techie."

Ju returned to Brazil after suffering medical malpractice and negligence connected to racism that left her disabled at CPMC Van Ness, in San Francisco.
Now confined to a wheelchair, the experience of constantly living with pain and the difficulty of finding adequate treatment led her back to her studies, resulting in the *MindNet solution.*

JUSTIFICATION FOR THE STUDY

From Experience to Solution: Zero-Distance Neurodigital Architecture

Upon becoming disabled during childbirth, I began to use a wheelchair and crutches for mobility, and my own body became, in a way, an object of study for me, for survival. From the experience of living with chronic pain for five years, I discovered how to adapt to and cope with this condition which, in some cases—and particularly in mine—can even resemble a form of torture, due to its intensity and persistence. The WHO estimates that a significant portion of the world's population, around 30%, also lives with chronic pain, generally defined as pain that persists or recurs for more than three months. Therefore, on a personal level, this study is born, like a lotus flower in the mud, from a great personal and global need.

My son and I are still awaiting the court's enforcement of our right to restitutio in integrum, the legal principle of full reparation, which seeks to restore, as far as possible, the situation that would have existed had the damage not occurred, through full compensation for the losses suffered. (CGC-23-11182, CGC-25-622102) With resources limited by the situation described above, and while we seek corresponding compensation for the damages suffered, I have begun the treatments available to me, even though these present risks and side effects, without necessarily providing a full recovery. After developing fibromyalgia as a consequence of the spinal and Sacral injury, I then set myself the goal of finding an alternative to deal with pain.

It was because of fibromyalgia that I understood that, to study pain, I needed to better understand the brain. That's where my interest in neuroscience began. And, since I couldn't leave my own career path behind, my technical background in telecommunications and computers naturally brought technology into this investigation.

It was from this encounter between my personal experience, neuroscience, and technology that the MindNet proposal emerged, the subject of patent applications before the INPI (Brazilian National Institute of Industrial Property) and the USPTO (USA), and which uses different technologies in unison to investigate the possibility of assisting the brain in one of the tasks that have become central to my research: modulating pain through the synchronization of neural states.

This study, therefore, arises from the need to establish a technically defined bridge between fields that have traditionally been investigated relatively independently in the fight against chronic pain: the neuroscience of neural transduction and representation processes and the telecommunications engineering responsible for transmitting information over long distances. In this way, MindNet represents the union between two fields that mark my own trajectory: from the perspective of neuroscience, an even deeper understanding of our minds and, through telecommunications, an even stronger connection to the Internet.

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"No one is free until everybody is free." — Fannie Lou Hamer, 1971.

1. Introduction

1.1 From Neural Acquisition to Brain-to-Brain

The present article describes the proposed solution, called MindNet, as a multimodal closed-loop neurodigital telecommunications architecture designed for the acquisition, processing, representation, transmission, and synchronization of information derived from neural states between individuals. The proposed architecture integrates principles of neuroscience, artificial intelligence, information theory, and telecommunications engineering, considering real-time functional MRI (rt-fMRI) and radiofrequency (RF) as mechanisms for functional acquisition, hyperpolarized carbon-13 magnetic resonance imaging (HP-^{13}C MRI) as a complementary modality for real-time metabolic characterization, and computational algorithms for noise reduction, feature extraction, neural decoding, and the construction of digital representations of brain states.

Following neural-to-digital conversion, these representations can be encoded, packetized, and transmitted through conventional telecommunications networks, including TCP/IP-based infrastructure, eliminating the need for the direct propagation of brain-generated or MRI fields between geographically separated individuals. Interindividual alignment methods, such as hyperalignment, are considered as potential mechanisms for establishing shared representational spaces and enabling the comparison of information across brains with individual functional organizations.
The study also proposes the implementation of MindNet based on existing precedents for its main functional components, including real-time fMRI processing, non-invasive neural decoding, brain-to-brain communication, Brainets, digital transmission of information derived from brain activity, including through DICOM-based imaging infrastructure, hyperscanning, and the alignment of neural representations across individuals.

The proposed architecture becomes bidirectional by incorporating reacquisition of the receiver's brain state and its concomitant use during the MRI/RF pulse sequence. Following information reception, the neural response is measured, represented, and compared with the sender's reference state, enabling the calculation of parameters that more accurately characterize their respective neural states. In this way, the study explains the proposed solution and discusses the technical implementability of the MindNet architecture, proposing that variables such as fidelity, end-to-end latency, neural bandwidth, error rate, and closed-loop gain be used as quantitative metrics to characterize system operation, evaluate efficiency, and guide the progressive optimization of MindNet as a neurodigital telecommunications system.

At the same time that MindNet collects new information derived from the brain activity of the Sender/Receiver, also processes this new information, converting it into digital representations and transmitting it through its technological architecture, which is the subject of patent applications at INPI and USPTO. In this architecture, RF, rt-fMRI, and HP-^{13}C MRI act as acquisition and characterization modalities for functional and metabolic signals, while artificial intelligence, integrated with real-time processing tools such as the Pyneal software, participates in the processing, noise reduction, feature extraction, and conversion of data acquired from a neural state. Once digitized and encoded, this information can be transported over the Internet, allowing people connected in different regions to exchange information derived from their neural states.

The various technological components necessary for the construction of this architecture already have scientific and technical precedents, as will be demonstrated throughout this article. Technologies such as MRI, real-time fMRI (rt-fMRI), and HP-^{13}C MRI demonstrate that physical and physiological phenomena of the organism can be obtained, detected, and converted into measurable signals, subsequently reconstructed and processed as digital information. During a magnetic resonance imaging acquisition, magnetic fields and radiofrequency pulses interact with the physical properties of tissues, and the resulting signals are detected by the equipment and computationally converted into data and images capable of providing information about the structures, functions, or metabolic processes of the human organism.

The MindNet architecture, therefore, extends the acquisition–digitization–transmission chain by treating information derived from neural states as elements of a neurodigital telecommunications system. Instead of limiting the flow to acquiring data from an individual and subsequently visualizing their images by a professional, MindNet proposes processing information derived from the sender's neural state, converting it into transmissible digital representations, transporting it over the Internet to another endpoint, and using a receiver interface to convert it into a biologically processable input for the receiver. Simultaneously, the receiver's neural response can be re-acquired, processed, and transmitted through the return channel. The differentiating factor

For decades, therefore, MRI systems have implemented a technological chain of physical interaction, acquisition, and processing of information regarding neural states: the equipment establishes controlled electromagnetic conditions, applies pulse sequences, detects the signals produced by the physical system under investigation, and transforms these signals into interpretable digital representations. Once produced, this information can be stored, shared, and transmitted between equipment, hospitals, doctors, and healthcare systems through digital infrastructures and standards such as DICOM (Digital Imaging and Communications in Medicine). In this way, information originating from an examination performed at a specific location can be converted into digital data and analyzed by professionals or computer systems located geographically distant from each other.

The proposed approach, therefore, does not simply consist of using MRI to send data—something that digital medical systems already do—but in integrating RF as a telecommunications system, neural acquisition, computational processing, artificial intelligence, telecommunications, receiver interface, and feedback in a bidirectional architecture designed for the exchange of information derived from neural states between geographically separated individuals.

Thus, the central argument is not that different functions necessary for the architecture—neural signal acquisition, real-time processing, digital representation, data transmission over networks, remote processing, and feedback—already have independent technological precedents. The scientific and engineering question posed by MindNet becomes how to integrate these components into an end-to-end architecture and mentally determine its performance, fidelity, latency, informational capacity, and closed-loop gain.

In this way, MindNet establishes a bidirectional transduction chain in which information from the sender, after being converted into a digital representation and transported through the telecommunications infrastructure, physically reaches the receiving system connected to MindNet. At this endpoint, the received information is decoded and converted, through the receiving interface, into a modality that is biologically processable by the receiver's nervous system. The subsequent neural response can then be acquired and analyzed by the architecture itself, allowing verification of whether the neural state produced in the receiver shows correspondence, similarity, or convergence with the reference representation derived from the sender. When the synchronization criteria previously established by the system are met, sender and receiver can be considered operationally synced-in within MindNet. In this sense, synced-in does not mean that the two brains become neurologically identical, but that their relevant neural representations have reached a measurable and previously defined degree of convergence within the representational space used by the system.

While the receiver receives and processes this information, MindNet can simultaneously acquire your brain response via rt-fMRI, converting the measurable signals associated with your neural state into new digital data. This data can be processed, encoded, and transmitted through the telecommunications infrastructure to the sender's endpoint, constituting a return channel. Thus, the geographical distance between individuals ceases, in principle, to be a limitation determined by the physical reach of brain signals or the magnetic fields produced by MRI equipment. After neural-digital transduction, long-distance communication depends mainly on issues specific to telecommunications systems and distributed processing, such as connectivity, bandwidth, latency, jitter, data integrity, security, and temporal synchronization. The digital representation derived from neural activity can therefore be transported between people connected to the network regardless of the physical distance between them, provided that each has the acquisition, processing, and interface components necessary for the architecture's operation.

MindNet therefore establishes a circuit in which digital information derived from the sender's brain state is transported to the receiver and converted into an input biologically processable, while the neural response produced in the receiver is acquired, converted into a new digital representation, and transmitted in the opposite direction. The receiver thus ceases to be merely the final destination of the communication and simultaneously functions as a new source of information for the circuit. This reciprocity allows acquisition, transmission, reception, neural response, verification, and feedback to occur continuously and potentially simultaneously, establishing the basis for bidirectional closed-loop neurodigital communication. In the proposed architecture, therefore, long-distance brain-to-brain communication does not depend on the direct transmission of neural activity through the space between individuals, but on the successive transduction between biological states and digital representations, using the telecommunications infrastructure as a connection channel between the two neural systems.

1.2 Contextualization and research problem

Functional neuroimaging, real-time computing, and brain-computer interfaces have made it possible to acquire brain signals, extract features, and transform some of these measurements into digital information. BOLD contrast established the basis of modern fMRI, while neurophysiological studies clarified its indirect relationship with neural activity, blood flow, and metabolism (Ogawa et al., 1992; Kwong et al., 1992; Logothetis et al., 2001; Hillman, 2014). Real-time fMRI systems and Pyneal have reduced the interval between acquisition and analysis, allowing results derived from recent volumes to be used during the session itself (Sitaram et al., 2017; MacInnes et al., 2020). The HP-13C enabled real-time acquisition of metabolic data. The research problem of MindNet is to determine whether these and other currently dispersed components can operate as a single architecture focused on enabling the acquisition, transport, and modulation of neural states. The central question is not whether brain signals can generate transmissible data, but whether acquisition, decoding, transmission, reception, modulation, and feedback can form a secure closed loop.

1.3 Chronic pain as a clinical and scientific motivation

According to the WHO, chronic pain, as an independent clinical condition, now affects 30% of people worldwide. This condition impacts mobility, sleep, autonomy, work, and social life (Treede et al., 2015; Nicholas et al., 2019). fMRI studies in this area have already identified multivariate signatures related to nociception and non-nociceptive components, while prolonged intracranial recordings have allowed for the estimation of spontaneous variations in chronic pain in everyday settings (Wager et al., 2013; Woo et al., 2017; Shirvalkar et al., 2023). In fibromyalgia, alterations in functional connectivity and amplified neural responses to stimuli demonstrate that the condition involves the reorganization of distributed networks, and not the isolated dysfunction of a single brain center (Cook et al., 2004; Napadow et al., 2010; Cifre et al., 2012). MindNet builds on these advances to investigate the representation, comparison, and adaptive modulation of neural states associated with pain, with the aim of establishing an alternative pathway for its control and treatment.

1.4 From neuroscience to neurodigital telecommunications

The most obvious candidate to assist in MindNet's distributed physical infrastructure are the radio base stations of cellular networks. 4G and 5G networks already constitute an extensive urban transmission and reception infrastructure, consisting of antennas, RF amplifiers, digital signal processing, synchronization systems, and network computing. In 5G, technologies such as Massive MIMO (Multiple-Input Multiple-Output) and beamforming add spatial control capabilities to the transmission, using multiple coordinated antenna elements to dynamically form and direct radio frequency beams.

Therefore, in contemporary cities, there already exists an infrastructure capable of generating, modulating, transmitting, receiving, and processing RF signals in different frequency bands.
Waves in the tens or hundreds of MHz range and at higher frequencies belong to the same physical domain of radio frequency engineering used in different telecommunications and magnetic resonance imaging applications, each with its own specific characteristics.

From an architectural standpoint, 5G/6G cellular infrastructure and software-defined radio frequency systems represent an important technological precedent for MindNet. Existing technology demonstrates that a city already possesses a substantial part of an “RF skeleton” capable of generating, controlling, directing, receiving, and transporting electromagnetic signals in a distributed manner. These capabilities do not, in isolation, constitute a neuroimaging system, but they provide engineering resources that can be incorporated and adapted to the physical layer of MindNet.

The central difficulty in remote neural acquisition, however, lies not only in the production or transmission of radiofrequency. The fundamental challenge is in detecting a response from the brain that is sufficiently specific and has an adequate signal-to-noise ratio to allow its identification, processing, and computational reconstruction. In conventional MRI systems, the receiver coils are positioned close to the body precisely because their geometry and proximity directly influence the sensitivity and signal-to-noise ratio of the acquired signal.

MindNet proposes to solve this issue through an architecture different from conventional MRI. Instead of relying on a scanner and a receiver coil positioned immediately around the head, the system combines a distributed RF infrastructure with computational processing and MindNet AI for signal detection and identification, noise reduction, interference correction, and reconstruction of neurodigital representations. In this model, artificial intelligence serves to enhance the computational capacity to separate, identify, and process information present in the detected signals, contributing to increased sensitivity and selectivity of the processing.

The proposal finds relevant technological precedents in low-field MRI, ultra-low-field MRI, atomic magnetometers, remote NMR detection, wireless RF coils, and inductive coupling systems. These developments demonstrate that certain elements of the physical architecture of magnetic resonance imaging can be rearranged into configurations different from that found in a conventional clinical scanner.

Urban telecommunications infrastructure can provide MindNet with a distributed RF layer, while the MindNet architecture adds the specific neurodigital acquisition layer, including control of physical parameters, detection, noise reduction, computational processing, and extraction of relevant information. The goal is to integrate principles and technologies already employed separately in telecommunications, magnetic resonance imaging, and computational processing to develop a specific remote neural acquisition system.

HP-^{13}C MRI adds a metabolic dimension to this architecture. Hyperpolarization substantially increases the detectable magnetization of ^{13}C nuclei, allowing for dynamic monitoring of the metabolism of labeled substrates, such as [1-^{13}C]pyruvate, and their metabolic products.

An important example uses pyruvate labeled with carbon-13 and hyperpolarized.
After administration, this substrate participates in metabolic processes and allows monitoring of products such as lactate and labeled bicarbonate. Park et al. demonstrated the application of HP-^{13}C brain MRI in patients using [1-^{13}C]pyruvate. The dynamic data allowed observation of pyruvate arrival and corresponding signals of its metabolic products, including lactate and bicarbonate. The study demonstrated the feasibility of using this approach for dynamic assessment of metabolism in the human brain.

This provides MindNet with two complementary classes of physiological information: a functional and hemodynamic dimension from rt-fMRI and a metabolic dimension from HP-1^{3}C MRI. The integration of these modalities allows for the structuring of a multimodal representation of the brain state, combining information associated with functional activity with information related to brain metabolism.

The possibility of extending the detection distance through this combination is a central engineering issue for MindNet. Hyperpolarization substantially increases the magnetization and, consequently, the detectability of ^{13}C. This gain in sensitivity is a relevant characteristic for investigating acquisition strategies at distances greater than those used in conventional configurations. Thus, hyperpolarization provides gains in detectability and long-distance acquisition.

In this sense, MindNet establishes a technological bridge between infrastructures that currently exist independently: on one hand, urban networks capable of producing, controlling, directing, receiving, and transporting RF signals; on the other, magnetic resonance imaging techniques capable of extracting functional and metabolic information from the organism. The technological gap lies in the connection between these two domains: establishing a remote acquisition chain with sufficient sensitivity, selectivity, and signal-to-noise ratio to detect useful brain information without reproducing the physical configuration of a conventional scanner. MindNet focuses precisely on this integration, combining distributed RF infrastructure, magnetic resonance imaging acquisition methods, hyperpolarization, computational processing, and artificial intelligence in an architecture designed for remote neurodigital acquisition.

1.5 Objective and scope of the study

The objective is to define MindNet as a neurodigital telecommunications architecture and establish a structured agenda for technical validation, to be implemented as soon as the author obtains the necessary financial restitution to enable the development of her technology. Regarding MindNet, the premise is its therapeutic application in modulating neural states between two individuals, with the aim of altering the perception and sensation of chronic pain in the recipient.[2] The architecture does not rely on entirely new technologies, but on the integration of phenomena, methods, and systems that have already been demonstrated independently. The scientific literature provides precedents for brain activity acquisition, real-time neuroimage processing, computational decoding of neural states, alignment of representations between individuals, digital transmission of brain-derived information, brain-to-brain interfaces, and the production of a measurable response in the recipient. MindNet organizes these components into a single neurodigital telecommunications chain and adds its own mechanisms for remote acquisition, multimodal integration, and closed-loop operation.

The process begins with acquisition. fMRI is a well-established technology for indirectly recording changes in brain activity through the BOLD signal. The foundational work of Ogawa et al. and Kwong et al. laid the groundwork for BOLD-fMRI, while Logothetis et al. investigated its relationship with neural activity. These studies establish the first necessary relationship for the architecture: changes in neural activity can produce physiological changes measurable by magnetic resonance imaging. MindNet uses this functional information as one of the sources to construct the representation of the brain state.

The acquisition can be processed in real time. MacInnes et al. developed Pyneal specifically for rt-fMRI processing, demonstrating a modular architecture capable of receiving data from the MRI system, processing it during acquisition, and making results available to other computational components. Pyneal also employs network communication between its components. Thus, the conversion of acquired neuroimages into usable computational information in real time already has an independent implementation.

HP-^{13}C MRI adds a second dimension. Park et al. demonstrated in the human brain the use of hyperpolarized [1-^{13}C]pyruvate and the dynamic acquisition of information related to pyruvate and its metabolic products, including lactate and bicarbonate. Hyperpolarization strongly increases the detectable magnetization of ^{13}C, allowing the monitoring of metabolic processes that would be much more difficult to observe by conventional MRI. In this way, MindNet can structure its multimodal acquisition from two different classes of information: rt-fMRI for functional and hemodynamic characteristics and HP-^{13}C MRI for metabolic characteristics.

The literature also demonstrates that the physical organization of an NMR experiment does not need to be restricted to the configuration of a conventional clinical scanner. Studies of

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Remote NMR detection has spatially separated the polarization, encoding, and detection stages. Ledbetter et al., for example, demonstrated remote NMR detection using a microfabricated atomic magnetometer, while Verpillat et al. performed detection with a magnetoresistive sensor. These experiments are particularly relevant as a physical precedent because they demonstrate that NMR components can be spatially rearranged and that different technologies can be employed for detection. They do not yet demonstrate human brain acquisition across a city; this distance extension, without physical transport of the magnetized sample, constitutes precisely one of the specific steps to be validated by MindNet.

After acquisition, the brain signal is transformed into a computational representation. This step also has strong precedent. Tang et al. demonstrated that non-invasive fMRI recordings can be used by computational models to reconstruct continuous semantic information from cortical representations. The result is particularly relevant because it shows that distributed fMRI patterns can be converted into a computational representation containing discriminable information about brain states, although performance is dependent on the individual and the model's training.

Two brains do not exhibit exactly the same spatial functional organization. The work of Haxby and colleagues on hyperalignment established a computational solution to this problem by demonstrating that individual functional patterns can be transformed into a shared, high-dimensional representational space. Instead of requiring a sender voxel to physically correspond to the same receiver voxel, the comparison can occur between functionally aligned representations. In MindNet, this principle provides a basis for converting the individual sender and receiver representations into a space in which their similarity and convergence can be calculated.

Once converted into digital information, the neural representation can use conventional TCP-IP telecommunications systems to traverse the distance between individuals. At this stage, the physical distance no longer depends on the propagation of the MRI signal between the two brains: what travels through the network is a digital representation of the acquired state. The literature on brain-to-brain interfaces has already demonstrated that signals derived from brain activity can be processed, encoded, and sent through digital networks to another location.

Pais-Vieira et al. demonstrated in 2013 a real-time brain-to-brain interface in which sensorimotor information obtained from an encoder animal was processed and used to influence a second decoder animal. The study demonstrated the transfer of behaviorally relevant information between two brains and constitutes one of the most important experimental precedents for the idea of an encoder chain.

This demonstration was later extended to humans. Grau et al. performed non-invasive brain-to-brain communication between geographically separated individuals, combining brain acquisition, binary encoding, internet transmission, and receiver stimulation. The study is especially relevant to MindNet because

This demonstrates that geographical distance can be overcome by the digital layer of communication, instead of requiring the original physical brain signal to travel that entire distance.

Rao et al. also demonstrated a non-invasive human brain-brain interface. The sender's brain activity was acquired and interpreted by a brain-brain interface.
A computer, transmitted over a network and used to produce a response in the receiver's motor system through transcranial magnetic stimulation. The authors characterized the result as a rudimentary form of direct brain-to-brain transmission. The importance of this experiment for MindNet lies in the complete demonstration of the sequence acquisition, interpretation , digital transmission , receptor interface and neural/behavioral response.

Stocco et al. advanced this principle using a brain-to-brain interface in a collaborative question-and-answer task. Five pairs of participants used the interface to identify an object through true or false answers, and the study included a sham condition. Performance was significantly superior to the control. This result is particularly important for the MindNet agenda because it demonstrates not only communication between two individuals, but also a methodology in which the effect of the interface can be compared to a sham condition.

Jiang et al. later expanded the concept with BrainNet, a brain-brain interface.
A brain involving multiple people jointly performing a task. The system integrated the acquisition, processing, transmission, and reception of neural information, showing that a brain communication architecture can function as a network and not just as an isolated connection between two individuals.

These experiments also clarify the final stage of MindNet: receiving digital data on a computer is not equivalent to the receiver's brain receiving that information. A transduction step is necessary between the digital representation and the nervous system. In the human experiments by Rao, Grau, Stocco, and Jiang, this function was performed by stimulation interfaces, primarily TMS, demonstrating that a representation derived from the sender can determine an intervention applied to the receiver and produce an observable response.

It is at this stage that MindNet presents an important architectural difference. The goal is not simply to reproduce EEG , Internet , TMS, but to integrate acquisition by RF-magnetic resonance, functional and metabolic characterization, artificial intelligence processing, neurodigital representation, telecommunications, and a layer of interaction with the receiver. Previous work demonstrates that physical interfaces can close the brain-computer-brain chain.

Finally, MindNet transforms this sequence into a closed loop. After interaction with the receiver, its brain activity is again acquired, processed, and converted into a \(Z_R\) representation, which can be compared to the \(Z_S\) representation of the sender. The receiver, therefore, ceases to be merely the final destination of the information: its response returns to the system and begins to determine the next operation. The work on rt-fMRI and neurofeedback provides precedents for brain acquisition and processing.

In real time, while brain-to-brain experiments demonstrate that neural information can travel across a digital chain and produce measurable responses in another individual. MindNet brings these two lines together in a sender and receiver cycle.

The proposed therapeutic application focuses this circuit on the victim of chronic pain. The premise is that a neural state of the sender can be acquired and represented by the system and used as a reference to promote and measure the modulation of the neural state of the receiver, seeking to modify their painful experience. The cited literature establishes experimental precedents for several components necessary for this chain, but the analgesic efficacy of MindNet integration constitutes a disruptive innovation.

Thus, MindNet's contribution lies in bringing together all these functionalities in a closed-loop neurodigital telecommunications architecture. BOLD-fMRI demonstrates functional acquisition; HP-^{13}C MRI adds metabolic characterization; Pyneal demonstrates real-time fMRI processing; neural decoding demonstrates the transformation of brain patterns into computational representations; hyperalignment offers a mechanism for comparison between individuals; remote NMR demonstrates that NMR functions can be spatially decoupled; the Pais-Vieira, Grau, Rao, Stocco, and Jiang interfaces demonstrate different forms of acquisition, digital transmission, and reception of brain-derived information. The next step is to determine the performance of the specific integration performed by MindNet and, finally, to establish its safety and clinical benefit in the modulation of chronic pain.

2. Safety, ethics and protection of participants

2.1 **“…to do good or to do no harm.”** - Hippocrates3

The safety during the use of MindNet technology must be analyzed within the technological context in which its architecture is embedded. Contemporary societies already operate continuously on electrical, magnetic, digital, and radio frequency infrastructures used by power grids, radio, television, mobile telephony, Wi-Fi, and other telecommunications systems. MindNet, therefore, does not introduce radio frequency or telecommunications as unprecedented physical phenomena into the human environment, but integrates acquisition, processing, transmission, and interaction technologies into a neurodigital telecommunications architecture. The prior existence of these infrastructures and their respective exposure standards constitutes an important technical and regulatory precedent for the quantitative definition of MindNet's operational safety parameters.

Therefore, the human implementation of MindNet should be guided by the principles of safety-by-design and risk minimization, with prior definition of exposure limits and other physical variables relevant to the configuration used. The system should incorporate independent interruption mechanisms, and safety should be determined by the incremental exposure attributable to MindNet and the specific characteristics of its use, and not by the mere presence of electromagnetic infrastructure in the environment.

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3 https://www.health.harvard.edu/blog/first-do-no-harm-201510138421

From a legal and bioethical standpoint, initial participation must be strictly voluntary and conditional upon the eligibility criteria defined in the protocol, medical and neurological evaluation, relevant imaging exams, and obtaining legally valid informed consent. The mere presence of an individual within the physical coverage area of a telecommunications infrastructure does not constitute consent, authorization, or waiver of any right. Technical connectivity does not equate to authorization for neural interaction. Individual activation of the technology must depend on an affirmative expression of will, authentication, authorization, and specific consent, while permanently preserving the right to refuse, withdraw, and disconnect.

In investigations involving human subjects, the protocol must comply with applicable participant protection standards and undergo corresponding ethical and regulatory review before implementation. Technical validation must include formal screening, standardized medical and neurological assessment, imaging studies when relevant, engineering and system safety assessment, informed consent, and systematic recording of adverse events, incidents, and near misses. When MRI systems are used, best practices and technical requirements applicable to the configuration employed must be observed.

In this way, MindNet's safety rests on four cumulative elements: physical technologies that have precedents of human use and known safety parameters for specific usage conditions; quantitative control of the incremental exposure produced by MindNet's specific configuration; medical, scientific, ethical, technical, and regulatory oversight during its validation; and individual autonomy protected by **informed consent, opt-in, right to withdraw ,** and right to disconnect.

3. MindNet concept and general architecture

3.1 Definition of MindNet In the

In the MindNet architecture, sender and receiver continuously participate in the same transduction circuit. In the sender, neuronal activity produces electrophysiological, metabolic, and hemodynamic changes that can be characterized by different acquisition and neuroimaging modalities, including rt-fMRI and HP-^{13}C MRI. During MRI acquisition, radiofrequency pulses physically interact with the nuclei present in brain tissue, while the resulting nuclear magnetization produces resonance signals detectable by the system. These signals are acquired, reconstructed, and computationally processed to derive a digital representation of the neural state.

MindNet proposes extending this relationship into a bidirectional architecture: the neural representation from the sender is converted into physical parameters of an RF interface designed to interact with the receiver's brain, while the resulting neural, metabolic, and hemodynamic response is simultaneously or immediately reacquired by the system. In this way, the interaction with the receiver and the acquisition of its response are integrated into the same operational cycle. The new information obtained is processed and compared to the representation from the sender, producing a measure of response, similarity, or convergence that returns to the system and guides the subsequent cycle. Thus, reception, transduction, acquisition, comparison, and feedback constitute a continuous closed-loop process.

with the therapeutic goal of promoting neuromodulation capable of interfering with the neural circuits associated with maintaining pain in the receiver and, in this context, interrupting or progressively reducing the chronic pain cycle of the other participant in the communication.

MindNet also includes several other components, mechanisms, stages, and application possibilities that could not be explored in this article without making it excessively long. In future works, each of these technologies and their respective functions within the architecture will be presented and discussed in detail and individually.

3.2 Digital-Physical-Biological Transduction

In the MindNet architecture, sender and receiver integrate a continuous circuit of neurobiological, physical, and digital transduction. In the sender, neural states emerge from the electrochemical activity of neuronal populations—including ionic fluxes, membrane potentials, synaptic transmission, and Ca^{2}ÿ-dependent signaling—and are associated with metabolic and hemodynamic changes mediated, among other mechanisms, by neurovascular coupling. These changes provide measurable physiological variables through neuroimaging: rt-fMRI dynamically characterizes changes related to BOLD contrast, while HP-^{13}C MRI adds information about specific metabolic processes. During MRI acquisition, radiofrequency fields interact with nuclear magnetization, and the resulting resonance signal is detected, reconstructed, and computationally processed. Pyneal and MindNet algorithms transform this data into a neurodigital representation \(Z_S(t)\), which can be encoded and transmitted over a telecommunications infrastructure.

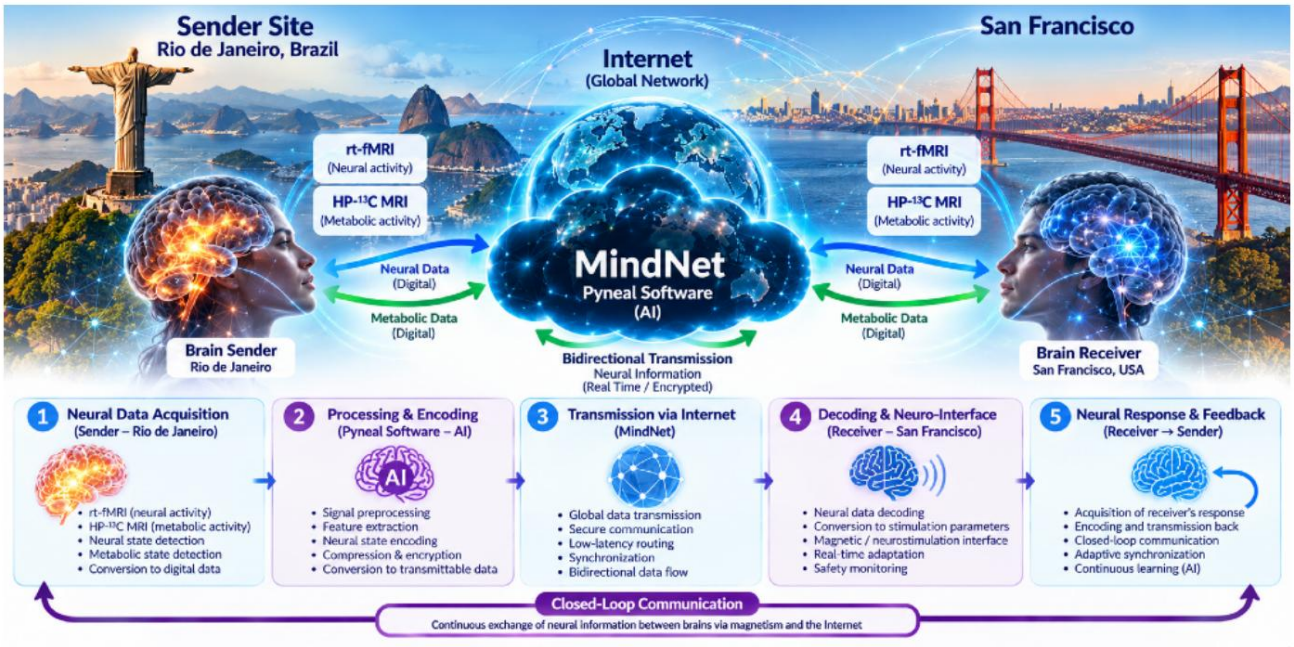
In the receiver, MindNet proposes to complement this chain with a transduction in the digital-physical-biological direction. The representation \(Z_S(t)\), received by the network, is converted into physical parameters of an RF interface designed to produce a selective neural interaction, while the resulting electrophysiological, metabolic, and hemodynamic response is continuously reacquired and converted into \(Z_R(t)\). The comparison between \(Z_S(t)\) and \(Z_R(t)\) provides a convergence or error signal that feeds the subsequent cycle. In this way, acquisition, transmission, transduction, reacquisition, comparison, and feedback are not isolated events, but temporally coupled components of the same closed circuit. In the proposed therapeutic application, this circuit aims to promote neuromodulation in the receiver and progressively modify the neural states associated with the maintenance of chronic pain, allowing the response produced to be continuously measured and used to adjust the subsequent interaction.

3.3 Closed-loop multi-loop architecture

The radiofrequency pulse used in RF-mediated MRI establishes a physical transmission-reception relationship with the spin system: RF interacts with nuclear magnetization and, after excitation, the evolution of this magnetization generates the resonance signal detected by the receiving system. In the MindNet architecture, this bidirectional relationship between RF and brain tissue is exploited as a physical basis for a two-way neurodigital transduction. With the aid of rt-fMRI for functional characterization, and HP-1^{3}C MRI for...

Using real-time metabolic characterization and artificial intelligence for encoding and decoding, the information derived from the sender's neural state is digitally represented, converted into physical parameters of an RF interface, and used to produce a corresponding neural response for the receiver. Simultaneously, or immediately after this interaction, the receiver's new functional and metabolic state is again acquired and processed, allowing its comparison with the sender's reference state and closing the communication and feedback loop.

3.4 General information flow



MindNet can be understood as a bidirectional chain of neurobiological, physical, and digital transduction, in which neural states are converted into transmissible neurodigital representations and, conversely, these representations are converted into physical parameters intended for interaction with the receiver's neural system, whose response is again acquired and incorporated into the closed loop.

4 Neuroscientific foundations of MindNet

4.1 The brain as a transduction system

In neuroscience terms, the chain begins with neuronal electrochemical activity, passes through brain metabolism and neurovascular coupling, becomes a measurable physical signal using neuroimaging techniques, and subsequently becomes a

computational representation. In the receiver, MindNet proposes to traverse part of this chain in reverse, establishing an integrated sequence of transductions.

Transduction is the process by which one form of energy, stimulus, signal, or information is converted into another form capable of being recognized, processed, or transmitted by a biological or physical system. In the human nervous system, transduction processes occur continuously and constitute fundamental principles of neural physiology.

When light reaches the retina, for example, photoreceptors convert light energy into electrochemical changes. When the skin is subjected to pressure, mechanoreceptors convert mechanical touch into electrical signals. When a neurotransmitter binds to certain neuronal receptors, a chemical event alters the ionic conductance of the membrane and, consequently, the electrical activity of the cell. The brain can therefore be understood as a complex biological transduction system, in which chemical, electrical, metabolic, hemodynamic, and physical phenomena remain interconnected.

In the MindNet architecture, sender and receiver continuously participate in a transduction chain that adds to these biological processes steps of acquisition through neuroimaging, computational processing, and telecommunications. In the sender, information originates from a physiological brain state, is converted into measurable signals, processed and encoded as a neurodigital representation, and transmitted through the telecommunications infrastructure. In the receiver, MindNet proposes to perform the complementary path, converting the received neurodigital representation into parameters of an interface intended for interaction with the neural system. The resulting brain response is continuously reacquired, processed, and compared to the reference state, closing the circuit through feedback.

Rao et al. demonstrated a non-invasive human brain-to-brain interface in which brain information from a sender was acquired by EEG, processed, and transmitted over the Internet, and subsequently used to produce a motor response in the receiver by transcranial magnetic stimulation (TMS). This experiment established a functional chain of brain acquisition, processing, telecommunication, physical transduction, and receiver response.

Stocco et al. advanced this principle by demonstrating interactive brain-to-brain communication in a question-and-answer task. Information from one participant was acquired, transmitted, and converted into stimulation in the other participant, allowing brain responses to influence subsequent interaction. The study also employed a sham condition, allowing them to distinguish performance associated with the interface from that observed in the control condition.

Jiang et al., through BrainNet, expanded this organization into a network involving multiple participants. The system combined brain recording, transmission

Digital and receiver stimulation allowed information from different brains to be used in a collaborative task.

MindNet extends this organization by proposing a multimodal and continuously closed chain, incorporating rt-fMRI for functional characterization, HP-1³C MRI for metabolic characterization, artificial intelligence for processing, encoding and decoding, telecommunications for transmission of the neurodigital representation, and a physical RF interface for the digital-physical-biological step in the receiver. The response produced in the receiver immediately returns to the system for new acquisition and processing, transforming communication into a continuous circuit of transduction, reacquisition, comparison, and feedback. In the proposed therapeutic application, this circuit is directed towards the neuromodulation of neural states associated with the maintenance of chronic pain in the receiver.

4.2 Our first neural state: pain in the sender

Let's assume the sender is experiencing pain. Pain doesn't correspond to a single wave, molecule, or brain region. It's a multidimensional experience resulting from the coordinated activity of multiple components of the nervous system, including peripheral nociceptive mechanisms, the spinal cord, the thalamus, and different cortical and subcortical regions involved in the sensory-discriminative, affective, cognitive, and autonomic dimensions of the painful experience.

In the brain, this state corresponds to distributed and dynamically organized patterns of neuronal and glial activity. Instead of a single "pain signal," different cell populations and circuits participate in the construction and maintenance of the neural state associated with the painful experience.

At the neuronal level, there is an uneven distribution of ions between the intracellular and extracellular environments. Sodium , potassium , calcium , and chloride selectively cross the cell membrane through different channels, pumps, and transporters, contributing to the establishment and modification of the membrane potential.

When excitatory stimuli produce sufficient depolarization to reach the threshold, voltage-gated sodium channels open rapidly.

It modifies the electrical potential of the membrane and produces the rising phase of the action potential. Then, the inactivation of Na channels and the opening of K channels favor the efflux of K, promoting membrane repolarization. The transmission of this activity along neural circuits also involves the release of neurotransmitters, the influx of Ca^{2} into presynaptic terminals, and the generation of postsynaptic responses.

The neural state related to pain is therefore associated with spatially and temporally organized patterns of electrochemical activity distributed among neuronal populations and their networks. Maintaining these processes requires energy to preserve and restore ionic gradients, sustain synaptic transmission, and maintain cellular homeostasis.

The relationship between action potentials, synaptic activity, and brain energy consumption was quantitatively analyzed by Attwell and Laughlin. The authors estimated the energy budget for signaling in cerebral gray matter and showed that a substantial portion of the energy is allocated to neuronal signaling, including action potentials and postsynaptic processes related to glutamate. This principle establishes a particularly important link for the MindNet architecture.

It is precisely in this transition that the distributed electrochemical state begins to produce physiological consequences that can contribute to its characterization by modalities such as rt-fMRI and, in another dimension, HP-1³C MRI. Neuroimaging does not directly measure each individual action potential; it allows access to aggregate physiological consequences related to the activity of these cell populations.

4.3 From electricity to chemistry — and back to electricity again

When an action potential reaches the presynaptic terminal of a neuron, another fundamental transduction step occurs. Depolarization of the membrane opens voltage-gated Ca²ÿ channels, allowing calcium to enter the presynaptic terminal.
The increase in intracellular Ca²ÿ concentration participates in the molecular mechanism that triggers the fusion of synaptic vesicles with the presynaptic membrane and the consequent release of neurotransmitters into the synaptic cleft.

Depending on the circuit involved, this communication can utilize glutamate, GABA, dopamine, norepinephrine, serotonin, acetylcholine, neuropeptides, and various other signaling molecules. After their release, neurotransmitters bind to receptors present on the postsynaptic cell and modify its activity.

In ionotropic receptors, neurotransmitter binding directly controls the opening or closing of ion channels, modifying membrane conductance and its electrical potential. In metabotropic receptors, binding activates intracellular mechanisms that may involve G proteins, second messengers, and biochemical cascades capable of modulating ion channels, enzymes, cellular metabolism, and other neuronal functions.

This conversion between electrical, ionic, and chemical phenomena constitutes one of the fundamental forms of transduction in the nervous system.

The energetic importance of this process is also consistent with Attwell's analysis and Laughlin, who constructed an energy budget for neural signaling in gray matter and attributed a substantial portion of the energy consumption to signaling.

neuronal, including action potentials and postsynaptic processes associated with glutamate.

Electrochemical and synaptic activity requires energy, and this metabolic demand is related to brain metabolism and neurovascular coupling, creating the physiological bridge between neuronal activity and variables that can be observed by BOLD-fMRI and, through distinct mechanisms, by HP-1^{3}C MRI.

4.4 Brain metabolism and energy demand

Brain activity requires energy. Synaptic transmission, restoration of ionic gradients, cellular transport, neurotransmitter recycling, and numerous other processes necessary for neural signaling increase the metabolic demand of functionally active regions.

The relationship between neuronal signaling and energy consumption was quantitatively analyzed by Attwell and Laughlin, who constructed an energy budget for signaling in cerebral gray matter. The study showed that action potentials and, particularly, processes related to synaptic transmission and postsynaptic currents represent important components of this energy consumption.

This activity involves not only neurons, but also astrocytes, endothelial cells, pericytes, and other components of the neurovascular unit. Glutamate, Ca^{2}, ATP, adenosine, nitric oxide, and various vasoactive mediators participate in a complex communication between neuronal activity, cellular metabolism, and cerebral circulation.

The participation of the pericitos in this process has particularly relevant importance. Hall et al. demonstrated that neuronal activity and glutamatergic signaling are associated with mechanisms capable of promoting capillary dilation through pericyte relaxation, providing evidence of their participation in the local regulation of cerebral blood flow and in the mechanisms related to the signals used by functional neuroimaging.

When activity in a particular brain region increases, neurovascular coupling produces a local vascular response. Regional cerebral blood flow is modified, and in this context, it is not simply a matter of "increased blood volume in the brain," but of regional changes in blood flow, volume, and oxygenation associated with neural activity.

The regional increase in blood flow can proportionally outweigh the local increase in oxygen consumption, modifying the ratio between oxyhemoglobin and deoxyhemoglobin. This alteration is particularly important for MRI because deoxyhemoglobin is paramagnetic and produces local changes in magnetic susceptibility that influence the resonance signal.

It is at this point that the transduction chain reaches a physical variable detectable by fMRI.

This relationship has a broad foundation. In 1992, Kwong et al. demonstrated signal changes by MRI associated with human sensory stimulation and local physiological changes related to brain activity. Around the same time, Ogawa et al. demonstrated contrast changes dependent on blood oxygenation during human visual stimulation, establishing fundamental bases for what later became known as BOLD-fMRI. Hillman subsequently reviewed the cellular, metabolic, and vascular mechanisms that connect neural activity and hemodynamic response.

For the construction of MindNet, this step is central: fMRI does not need to directly detect each action potential. Neuronal activity triggers a succession of electrochemical, metabolic, vascular, and magnetic transductions that produce a measurable physical signature. rt-fMRI allows for dynamic monitoring of this functional signature, while HP-1^3C MRI can add a complementary metabolic dimension to the characterization of the brain state.

4.5 How is the neural state read?

Contrast-enhanced BOLD fMRI does not directly detect each action potential of each neuron. It detects hemodynamic changes related to blood oxygenation that indirectly accompany changes in neural activity.

One of the fundamental experiments to establish this relationship was performed by Logothetis et al., who simultaneously recorded intracortical neural signals and BOLD responses in the visual cortex. The study compared local field potentials (LFPs), multi-unit activity, and BOLD responses, demonstrating a particularly close relationship between BOLD and local field potentials. This result provided an important neurophysiological basis for interpreting fMRI as an indirect measure of the activity of neural populations, strongly related to synaptic and intracortical processing.

Hillman describes this relationship within neurovascular coupling: changes in neural activity trigger cellular and vascular responses that locally modify blood flow, volume, and oxygenation. Because deoxyhemoglobin (HbR) is paramagnetic, changes in its concentration modify local magnetic susceptibility and, consequently, the BOLD signal.

Therefore, when MindNet uses rt-fMRI, there is an intermediate physiological chain between neural activity and the acquired data. Neuronal activity modifies energy demand; neurons, astrocytes, and vascular components participate in neurovascular coupling; blood flow and oxygenation are modified; the HbOÿ/HbR ratio changes; these changes modify local magnetic properties; and fMRI acquisition transforms these variations into data that can be computationally processed.

The sequence can be represented directly as follows.

The information originally expressed in the distributed electrochemical dynamics of neural networks thus acquires a measurable hemodynamic representation.
This representation is not a direct copy of the action potentials: it is a physiological consequence spatially and temporally related to the activity of the neural populations that originated it.

The work of Ogawa et al., Kwong et al., Logothetis et al., Hall et al., and Hillman together form a particularly solid foundation for this stage of the MindNet architecture: Ogawa and Kwong established experimental foundations for oxygenation-dependent contrast; Logothetis linked BOLD mind and neural activity; Hall demonstrated microvascular mechanisms involving pericytes; and Hillman integrated the cellular, metabolic, and vascular mechanisms of neurovascular coupling.

4.6 The metabolic contribution of MindNet

HP-^{13}C MRI adds another level to the physiological formation of the MindNet architecture.
While the BOLD contrast of rt-fMRI primarily provides information related to hemodynamic and oxygenation changes associated with brain activity, hyperpolarized carbon-13 imaging allows for monitoring certain metabolic transformations with substantially increased sensitivity.

One of the main examples uses hyperpolarized [1-^{13}C]pyruvate. Pyruvate participates in metabolic pathways whose labeled products can be dynamically tracked.
Among them is [1-^{13}C]lactate, produced by metabolic exchange catalyzed by lactate dehydrogenase (LDH). ^{13}C-bicarbonate, related to the oxidative metabolism of pyruvate via pyruvate dehydrogenase (PDH), can also be detected.

Park et al. demonstrated the feasibility of brain metabolic imaging with hyperpolarized [1-^{13}C]pyruvate in humans. Dynamic acquisition allowed observation of pyruvate arrival in the brain and corresponding signals of its metabolic products, including lactate and bicarbonate, demonstrating the possibility of spatially and temporally characterizing aspects of brain metabolism by HP-^{13}C MRI.

MindNet thus comes to conceptually have two complementary classes of information.

The combination is relevant because one modality predominantly characterizes the hemodynamic consequences of neural activity, while the other adds dynamic information about metabolism. In MindNet, this data can be integrated computationally to construct a multimodal representation of the brain's physiological state.

HP-1³C MRI constitutes a metabolic characterization channel within the architecture. It is not currently an established technology for transmitting neural content between individuals. In MindNet, however, its function is to complement the characterization of the brain state and also to allow monitoring of metabolic evolution throughout the closed loop.

4.7 The biophysical interaction between technology and the brain

Here we move from neurophysiology to the biophysics of magnetic resonance imaging. The brain contains a large amount of water and therefore a high concentration of hydrogen nuclei (^1H). These nuclei possess spin and magnetic moment. When the individual is subjected to the main static magnetic field of MRI, called Bÿ, a small difference occurs between the populations of possible energy states, producing a resulting macroscopic magnetization oriented predominantly in the direction of Bÿ.

At the same time, the nuclear magnetic moments exhibit precession around the direction of Bÿ. The frequency of this precession depends on the intensity of the magnetic field and the gyromagnetic ratio of the nucleus, and is determined by the Larmor relation.

For hydrogen, ÿ/2ÿ is approximately 42.58 MHz/T. Thus, in a 3 T instrument, for example, the Larmor frequency of the protons is close to 127.7 MHz.

The MRI system then produces a radiofrequency magnetic field, called Bo, applied transversely to Bo and with a frequency close to the resonance frequency of the nuclei to be excited. When the resonance conditions are met, energy transfer occurs from the RF field to the spin system, modifying the orientation of the macroscopic magnetization.

The amplitude and duration of the RF pulse, along with other sequence parameters, determine the magnetization rotation angle, called the flip angle. In this way, pulses corresponding to 90°, 180°, or other angles used in different MRI sequences can be produced, for example.Therefore, at this stage there is a well-established physical transduction:

After the pulse ends, this magnetization evolves and progressively returns to equilibrium through relaxation processes. The precessive transverse magnetization generates variable magnetic flux and induces electrical voltage in the receiving coil, allowing the detection of the MR signal. The chain can then be extended:

After the pulse ends, this magnetization evolves and progressively returns to equilibrium through relaxation processes. The precessive transverse magnetization generates variable magnetic flux and induces electrical voltage in the receiving coil, allowing the detection of the MR signal.

This factor is especially important for describing MindNet because it demonstrates that, within MRI, a bidirectional physical chain of transmission and reception already exists: the equipment transmits RF to interact with the spin system and subsequently receives the signal produced by the evolution of this magnetization. This, in itself, establishes the physical basis of RF-tissue-signal transduction upon which the MindNet architecture proposes to add functional acquisition, neurodigital processing, telecommunications, and closed-loop connectivity.

The classic work of Ogawa et al. and Kwong et al. demonstrated that this MRI physics can be used to detect signal changes associated with human brain activation, establishing experimental foundations for BOLD contrast-based fMRI.

4.9 “More love, please…” (Brazilian saying)

From this point, the data from the different MindNet modalities can be subjected to computational processing. In rt-fMRI, this processing can include motion correction, noise reduction, normalization, feature extraction, spatial and temporal pattern identification, and neural decoding. In HP-

1^3C MRI, and it is possible to process metabolic data, separate pyruvate signals and their products, and extract metabolic characteristics. It is important to distinguish these two pipelines because Pyneal was developed specifically for rt-fMRI, and not as HP-1^3C processing software.

Pyneal enters this layer as an open infrastructure for real-time fMRI acquisition and processing. MacInnes et al. developed the system in Python with a modular architecture, customizable analysis pipelines, and communication between its computational components, allowing results obtained during acquisition to be made available in real time for external applications, including neurofeedback paradigms.

The next step involves transforming the acquired data into computational representations of the brain state. Tang et al. provided a particularly important precedent by demonstrating a non-invasive decoder capable of reconstructing continuous language from cortical semantic representations recorded by fMRI. The result demonstrates that distributed fMRI patterns can contain sufficiently structured information to allow a computational reconstruction of semantic content.

Thus, the sender's physiological state successively traverses different domains:

From this point on, a conceptually important change occurs: distance is no longer necessarily treated as propagation of the original physiological signal. Once a digital representation is constructed, it can be encoded, packetized, and transported over conventional TCP/IP-based networks.

In the example cited earlier, in which the Sender suffers from chronic pain, the Sender's initial state is a painful experience. MindNet seeks to acquire measurable characteristics of the brain state associated with this experience and convert them into a neurodigital representation. This is not to say that there is a single "pain code"; the representation can integrate multiple distributed functional and metabolic characteristics.

The receiver's brain does not literally receive the ions, neurotransmitters, metabolic molecules, action potentials, or private experience of the sender's brain. What travels through the telecommunications network is a digital representation derived from the brain state. The MindNet architecture proposes that this representation be used by the receiver's system as reference information to produce a subsequent neural response.

Tang et al. provide a precedent for part of this operation by demonstrating that even distributed semantic representations recorded by fMRI can be used computationally to reconstruct continuous language. Haxby et al. add another fundamental component: two people can have distinct cortical topographies and yet their patterns can be transformed into a common representational space in which shared information can be compared.

From this interaction, the receiver produces its own brain response. If this response is related, for example, to the perception and evaluation of the other's suffering, circuits associated with affective processing, social cognition, and components of empathy may be recruited. This new state is biologically unique to the receiver and, therefore, does not need to be identical to the state originally acquired in the sender.

The receiver doesn't "feel" pain.

In MindNet's closed-loop architecture, however, communication does not end at that point. The receiver's new neural state is again acquired, processed, and converted into a neurodigital representation. At this moment, a functional role reversal occurs: the receiver becomes the sender. The information that returns represents a neural state transformed by the response of the second brain—in this example, a response associated with empathy and useful for modulating the sender's pain.

In this way, the circuit ceases to be merely a unidirectional transmission of brain information and becomes a recursive interaction between two neural systems. The first brain provides the initial state; the second produces its own response; this response returns as new information to the circuit. In the proposed example, what returns is not simply the originally transmitted pain, but a different neural state—an empathic response. Human.

5 Acquisition and characterization of neural states

5.1 Where MindNet began

Radiofrequency has been extensively studied and used for pain treatment.
However, the term radiofrequency encompasses many distinct modalities, with different mechanisms, application parameters, and therapeutic objectives.

In continuous or thermal radiofrequency, for example, RF energy is applied through an electrode positioned close to the selected neural structure, producing controlled heating and allowing the ablation of structures involved in the nociceptive transmission of pain. The use of radiofrequency for chronic pain has extensive clinical literature, including applications in facet joint pain and other musculoskeletal conditions, and it was there that the author began her research, encouraged by her knowledge in the field of Telecommunications.

Other analyses provide complementary evidence; for example, Shi et al. (2016), in a meta-analysis of 12 randomized clinical trials involving 592 patients, evaluated the efficacy and safety of PRF in different neuropathic pain conditions and found favorable results in certain indications, particularly in post-herpetic neuralgia. These results reinforce that controlled exposure to pulsed radiofrequency can produce clinically measurable effects on pain of a nociceptive nature.

Particularly relevant to the proposal of a non-invasive approach against chronic pain is transcutaneous pulsed radiofrequency (TcPRF). Asimakopoulos, Tsaroucha, and Rekatsina (2026) conducted a systematic review of eight randomized clinical trials involving musculoskeletal and neuropathic conditions of chronic pain. Most of the studies analyzed found a reduction in pain intensity, with particularly consistent results in some sham-controlled events.

These studies establish a particularly important precedent for MindNet architecture. Vanneste et al. (2020), Shi et al. (2016), and the trials synthesized in their respective reviews on PRF demonstrate that the application of radiofrequency to nervous system structures has already been extensively investigated as an analgesic neuromodulation tool. Asimakopoulos, Tsaroucha, and Rekatsina (2026) add a particularly relevant element by demonstrating that the transcutaneous and non-invasive application of PRF has also been evaluated in randomized clinical trials.

Therefore, the relationship is:

Radiofrequency ÿ interaction with the neural system ÿ neuromodulation ÿ modification of nociception ÿ alteration of pain.

It has independent experimental and clinical precedents.

In the MindNet architecture, this principle is extended to a different function. The proposal consists of integrating RF acquisition into a neurodigital architecture, in which information related to the sender's brain state is acquired, processed, converted into computational representations, transmitted through the telecommunications infrastructure, and used as a reference for interaction with the receiver's neural system. The resulting response is again acquired and processed, allowing its comparison with the reference state and the continuity of the circuit.

In this context, the sequence proposed by MindNet can be represented as:

neural state of the sender ÿ acquisition ÿ neural decoding ÿ neurodigital representation ÿ
telecommunications ÿ RF interface ÿ receiver neuromodulation ÿ new acquisition ÿ
new representation ÿ comparison ÿ feedback

The possibility of using radiofrequency to produce neuromodulatory effects associated with pain reduction has a basis; Vanneste et al. (2020) document this precedent in different neuropathic conditions; Shi et al. (2016) present evidence from randomized trials; and Asimakopoulos, Tsaroucha and Rekatsina (2026) extend a vast body of evidence to non-invasive transcutaneous application.

This literature converges with other independent components that underpin the MindNet architecture. Ogawa et al. (1992), in their fundamental experiments on blood oxygenation-dependent contrast, and Kwong et al. (1992), in demonstrating detectable human brain functional changes by MRI, established experimental foundations for functional acquisition based on BOLD contrast.

Logothetis et al. (2001), through simultaneous recordings of intracortical and BOLD neural activity, provided a neurophysiological basis for relating neural activities to the signal measured by fMRI.

MacInnes et al. (2020), in turn, developed Pyneal as an open-source computational infrastructure for real-time fMRI processing, demonstrating the possibility of integrating acquisition, processing, and dissemination of results during the experiment. Tang et al. (2023) demonstrated that distributed semantic representations recorded by fMRI can be used by a non-invasive decoder to reconstruct continuous language. Haxby et al. (2020) demonstrated, through hyperalignment, that functional patterns of different individuals can be transformed into a shared space, preserving common information among individuals.

Furthermore, Rao et al. (2014) demonstrated a non-invasive human brain-to-brain interface in which EEG-derived information was transmitted over the Internet and used, in conjunction with transcranial magnetic stimulation (TMS), to produce a response in the receiving participant. Grau et al. (2014) demonstrated non-invasive brain-to-brain communication.

Invasive interaction between geographically separated participants, combining brain acquisition, digital transmission, and stimulation at the receiver. Stocco et al. (2015) advanced to human brain-to-brain interaction in a collaborative task, including a sham condition. Jiang et al. (2019), in turn, demonstrated BrainNet, a brain-to-brain interface that enabled collaboration between participants. These experiments constitute independent precedents for the integration between brain signal acquisition, remote digital transmission, and interaction with another participant.

It is precisely at the convergence of these precedents that MindNet's proposal is situated. The objective that motivated the author's research, which began in RF, was to investigate a non-invasive alternative for pain modulation, designed to minimize adverse effects, evolving from the integration of technologies and principles that already have independent precedents in medicine, neuroscience, neuroimaging, radiofrequency, computational processing, and telecommunications. The author's prior experience in the telecommunications field contributed to expanding this investigation, which began 6 years ago when she and her son left the delivery room with sequelae. MindNet, instead of considering brain acquisition, processing, transmission, and neuromodulation as isolated items, organizes them as components of the same architecture. And even this inspiration came from the telecommunications field, whose architecture is, most of the time, the result of a set of many integrated platforms, technologies, and solutions through *software.*

Thus, the proposed innovation does not lie in the assertion that each physical or neurobiological phenomenon used by MindNet is new. On the contrary, its foundation derives precisely from the existence of independent precedents for different components. Ogawa et al. (1992), Kwong et al. (1992), and Logothetis et al. (2001) substantiate the relationship between brain activity and functional acquisition by MRI; MacInnes et al. (2020) provides a precedent for real-time fMRI processing; Haxby et al. (2020) for the computational alignment of representations between individuals; Tang et al. (2023) for neural decoding of distributed information recorded by fMRI; Rao et al.
(2014), Grau et al. (2014), Stocco et al. (2015) and Jiang et al. (2019) for different forms of brain-to-brain communication mediated by digital systems; and Vanneste et al. (2020), Shi et al. (2016) and Asimakopoulos, Tsaroucha and Rekatsina (2026) for the use of radiofrequency as a neuromodulation tool associated with pain.

One of MindNet's innovations lies in the integration of these components into an architecture designed to acquire, represent, transmit, compare, and modulate neural states between individuals, with chronic pain as one of its main therapeutic motivations.

5.2 Urban telecommunications infrastructure and remote acquisition at MindNet

The most obvious candidate to assist in MindNet's distributed physical infrastructure are the radio base stations of cellular networks. 4G and 5G networks already constitute an extensive urban transmission and reception infrastructure, comprised of antennas, RF amplifiers, digital signal processing, synchronization systems, fiber optics, backhaul, and network computing. In 5G, technologies such as Massive MIMO (Multiple-Input Multiple-Output) and beamforming add spatial control capabilities to the transmission, using multiple coordinated antenna elements to form and direct beams of signal.

radio frequency dynamically. Khwandah et al. (2021), for example, describe Massive MIMO and 3D beamforming as technologies capable of using multiple antennas to concentrate radiation towards users and improve the spatial and spectral efficiency of 5G networks.

Therefore, in contemporary cities, there already exists an infrastructure capable of generating, modulating, transmitting, receiving, and processing RF signals in different frequency bands. Waves in the tens or hundreds of MHz and at higher frequencies belong to the same physical domain of radio frequency engineering used in different telecommunications and magnetic resonance applications, each with its own specificities. Darnell et al. (2019), for example, demonstrated an integrated coil capable of operating simultaneously with currents at the Larmor frequency for MRI and in a wireless communication band, establishing a concrete precedent for the coexistence of magnetic resonance and wireless communication functions in an RF architecture.

From an architectural point of view, 5G/6G cellular infrastructure and software-defined radio frequency systems represent an important technological precedent for MindNet. Existing technology demonstrates that a city already possesses a substantial part of an “RF skeleton” capable of capturing and transporting electromagnetic signals in a distributed manner. In the case of 5G, Khwandah et al. (2021) show that Massive MIMO systems allow for the coordination of numerous antenna elements and spatial control of transmission through beamforming.

The central difficulty in remote neural acquisition, however, lies not only in the production or transmission of radiofrequency. The fundamental challenge is in *detecting a response from the brain that is sufficiently specific and has an adequate signal-to-noise ratio to allow its identification,* processing, and computational reconstruction. In conventional MRI systems, the receiver coils are positioned close to the body precisely because their geometry and proximity directly influence the sensitivity and signal-to-noise ratio of the acquired signal.

MindNet proposes to solve this issue through an architecture different from conventional MRI. Instead of relying on a scanner and a receiver coil positioned immediately around the head, the system combines a distributed RF infrastructure, which, together with rt-MRI, HP-13C, and MindNet AI, works to detect and identify the signal, reduce noise, correct interference, and reconstruct neurodigital representations. In this model, artificial intelligence serves to increase the computational capacity to separate, identify, and process information effectively present in the detected signals, contributing to greater sensitivity and selectivity. The software enhances and refines the result that the simple connection between the technologies would not be able to deliver.

The proposal finds relevant technological precedents in low-field MRI, ultra-low-field MRI, atomic magnetometers, remote NMR detection, wireless RF coils, and inductive coupling systems. Savukov and Romalis (2005), for example, demonstrated the detection of NMR signals using an atomic magnetometer and discussed its possible use in multichannel systems for three-dimensional MRI. The *signal* and the principle

Technological and scientific advancements have therefore been demonstrated. Ledbetter et al. (2008), in turn, demonstrated remote detection of NMR using an atomic magnetometer, establishing a precedent for the spatial separation of NMR encoding and detection functions.

Darnell et al. (2019) added another particularly relevant precedent by developing an integrated RF/wireless coil capable of performing MR image acquisition and wireless communication simultaneously. The same architecture allowed current circulation at the Larmor frequency and in a wireless communication band, while maintaining the coil's signal-to-noise ratio. The authors further demonstrated image acquisition and wireless data transfer from localized Bÿ in an integrated configuration.

These developments therefore demonstrate that the scientific principle of reorganizing and integrating different RF, acquisition, encoding, and telecommunications components has experimental precedents. The urban telecommunications infrastructure may already possess part of the distributed RF and digital transport layer, while MindNet AI could add the necessary software to obtain, with greater sensitivity and computational selectivity, information that might previously have gone unnoticed, including control of physical parameters, detection, noise reduction, and extraction of relevant information.

The goal is to integrate systems already used separately, a fairly common characteristic in telecommunications, which frequently uses different platforms, systems, and technologies to develop specific products, connecting their components around a single operational purpose. In this sense, the author's experience in creating and implementing telecommunications products contributed to making the architectural design of MindNet intuitive: different technologies do not need to perform the entire system function in isolation; they can constitute specialized layers of the same network.

HP-^{13}C MRI adds a particularly important possibility to this architecture due to the large increase in sensitivity provided by hyperpolarization for the detection of ^13C nuclei. The literature on HP-^{13}C demonstrates a significant increase in magnetization and detectability of the metabolic signal.

HP-1^{3}C MRI also adds a metabolic dimension to this system. An important example uses hyperpolarized [1-1^{3}C]pyruvate, which participates in metabolic processes and allows monitoring of lactate and bicarbonate to gather relevant information.

Independent results from Miloushev et al. (2018) also demonstrated metabolic imaging of the human brain using hyperpolarized [1-^{13}C]pyruvate, including dynamic acquisition and detectable production of [1-^{13}C]lactate in the brain, including in brain tumors. These studies reinforce the use of HP-^{13}C as a modality capable of adding dynamic metabolic information to brain characterization.

This provides MindNet with two complementary classes of physiological information: a functional and hemodynamic dimension derived from rt-fMRI and a metabolic dimension.

derived from HP-1³C MRI. Park et al. (2018) and Miloushev et al. (2018) provide particularly important experimental precedents for this second layer of information. Similarly, Savukov and Romalis (2005) demonstrated increased sensitivity of NMR detection by magnetometry, and Ledbetter et al. (2008) demonstrated remote NMR detection.

In this sense, MindNet establishes a technological bridge between two infrastructures that already exist independently: on the one hand, urban networks capable of producing, directing, receiving, and transporting RF signals and digital data, as demonstrated by the development of Massive MIMO and beamforming described by Khwandah et al. (2021) and Senger and Malik (2022); and on the other hand, magnetic resonance techniques capable of extracting functional and metabolic information from the organism, including the HP-^{13}C systems demonstrated by Park et al. (2018) and Miloushev et al. (2018). Among these domains are also precedents for the reorganization of NMR detection, such as Savukov and Romalis (2005), Ledbetter et al. (2008), and Verpillat et al. (2008), and for the integration between MRI RF and wireless communication, such as Darnell et al. (2019).

The technological gap that MindNet fills lies in the connection between these domains: producing a remote acquisition chain with sufficient sensitivity and selectivity to detect useful brain information without the physical setup of a conventional scanner. It is in this connection that MindNet proposes to integrate these infrastructures through proprietary software; MindNet AI works to generate neurodigital representation in a single system.

The technological gap that MindNet fills lies precisely in the connection between these domains: producing a remote neural acquisition chain with sensitivity, selectivity, spatial and temporal resolution, and a signal-to-noise ratio low enough to detect useful brain information without the physical setup of a conventional scanner.

The studies cited provide precedents for different components of this architecture, but it is our integration—distributed RF infrastructure, physical acquisition, MindNet AI, neurodigital representation, and transport over the telecommunications network—that constitutes the specific and complete solution to help us in the fight against chronic pain.

5.3 MindNet AI: Artificial intelligence as a layer for neurodigital translation, reconstruction, and synchronization.

MindNet AI constitutes the central

computational layer of the MindNet architecture. As defined in the previously presented architecture, it connects physical acquisition, neuroimaging, signal processing, telecommunications, and feedback in a closed loop. In the telecommunications field, we are accustomed to creating software quite frequently to integrate, correct, decode, and refine. In functional terms, MindNet acts as a neural codec, transforming data derived from the brain into neurodigital representations suitable for analysis and transmission and, in the reverse direction of the circuit, interpreting the acquired response from the receiver to compare it to the sender's reference state.

MindNet AI's primary role is in data acquisition and pre-processing.
Data from rt-fMRI and HP-1³C MRI show different spatial structures.

Temporal, hemodynamic, and metabolic. MindNet AI participates in artifact correction, noise reduction, interference identification, signal refinement, and reconstruction. In the remote acquisition architecture proposed by MindNet, this function becomes particularly important: algorithms can search for relevant structures in signals with low signal-to-noise ratios and separate informative components from interference—in this case, information that, upon reaching the receiver, modulates its pain.

The state of the art in AI applied to fMRI offers important precedents for this function and has been employed for brain data modeling, while learning algorithms seek to improve tasks to obtain transferable neural representations.
Yang et al. (2026) identify four main paradigms in the use of Transformer architectures for fMRI data analysis: temporal modeling, spatial modeling, joint spatiotemporal modeling, and self-supervised learning, highlighting their ability to capture long-distance signals in brain data.

A particularly significant development for MindNet is NeuroSTORM. In 2026, this foundational fMRI model was pre-trained directly on 4D volumetric data, corresponding to 28.65 million fMRI frames from over 50,000 participants, spanning multiple centers and individuals aged 5 to 100 years. NeuroSTORM learns generalizable spatiotemporal representations and subsequently adapts them to different tasks, demonstrating superior performance to comparison methods in five downstream applications (NeuroSTORM, 2026).

This result provides an important contemporary precedent for the design of a MindNet AI capable of learning generalizable neural representations, rather than treating the brain data of each individual or dataset as a completely independent computational problem.

The second function is neural decoding itself. Tang et al. (2023) demonstrated that a non-invasive decoder can reconstruct continuous language from cortical semantic representations obtained by fMRI. The experiment does not represent unrestricted reading of mental states and required specific participant training, but it demonstrates a fundamental principle for MindNet: information distributed in fMRI patterns can be converted by AI into a different and computationally manipulable informational representation. In the case of application to pain, the learning curve tends to be less laborious, since the information for pain modulation in the brain does not include language, although it is a feature that will be used in the future for communication and research. The advancement of the area since then has been rapid; Wang et al. (2025), in a review on linguistic neural decoding, describe the increasing use of deep learning to convert neural activity into linguistic representations and simultaneously analyze the still existing problems of generalization, interindividual variability, and interpretation.

The same principle has already reached the visual domain. Takagi and Nishimoto (2023) used latent diffusion models to reconstruct images from brain activity recorded by fMRI, demonstrating that latent representations of generative models can act as a bridge between brain patterns and complex computational representations. Scotti et al. (2023), using MindEye, combined contrastive learning, diffusion priors, and multimodal latent spaces as CLIP to perform image retrieval and reconstruction from fMRI. MindEye also demonstrated a property

Particularly relevant to MindNet: brain embeddings could be mapped to a previously learned multimodal latent space, preserving sufficiently specific information to distinguish similar images. The Voxel and the new pixel.

Another interesting issue to address is the variability between brains. Haxby et al. (2020), through hyperalignment, demonstrated that individual functional topographies can be transformed into a common high-dimensional representational space. In MindNet, this principle allows for the design of specific transformations for sender and receiver, so that two anatomically different patterns can be compared in a shared computational space. The state of the art is moving precisely towards models capable of learning transferable representations between individuals; Sümer-Arpak et al. (2026) highlight foundation models, self-supervised learning, Transformers, and shared semantic spaces as emerging directions for non-invasive neural decoding.

MindNet AI is also a great ally after transmission. The receiver is not a passive destination. Its new state is reacquired and transformed into a representation \(Z_R(t)\), which can be compared to the representation \(Z_S(t-\Delta)\) of the sender. The AI can estimate the nature of the information taking into account the latency of acquisition, the network, and the brain's own physiology. In this way, MindNet AI ceases to be just a decoder and also becomes the computational controller of the circuit.

This concept is compatible with a broader shift in the state of the art from AI to neuroscience. Mathis and Mathis (2026) describe the convergence of discriminative models to jointly learn brain dynamics and infer behavioral logic. Sümer-Arpak et al. (2026), in turn, show that foundation models are driving neural decoding of specific classifiers toward learning scalable and semantically structured representations, although challenges remain related to noise, inter-individual variability, data volume, interpretability, standardization, and expectations. The author believes that it will never be possible to encapsulate human consciousness, which makes neuroscience even more interesting. MindNet is here to facilitate communication and connection.

Thus, MindNet AI can be defined as an adaptive artificial intelligence architecture responsible for converting brain signals into neurodigital representations, aligning representations between individuals, preserving distinguishable information during transmission, interpreting the receiver's response, and controlling feedback through the tools available within each layer.

The state of the art separately demonstrates capabilities increasingly closer to the functions required for this architecture: Tang et al. (2023) for semantic decoding; Takagi and Nishimoto (2023) and Scotti et al. (2023) for generative reconstruction and latent spaces derived from fMRI; Haxby et al. (2020) for interindividual alignment; MacInnes et al. (2020) for operational processing of rt-fMRI; NeuroSTORM (2026) for large-scale fMRI foundation models; and Sümer-Arpak et al. (2026) for the emergence of foundational models in non-invasive decoding. MindNet AI proposes to combine these capabilities by adding RF, rt-fMRI/HP-^{13}C MRI, and integration with

Telecommunications and the ongoing comparison between sender and receiver in the fight against pain.

5.4 Pyneal and DICOM in the MindNet architecture

In the MindNet architecture, Pyneal can occupy a strategic position between rt-fMRI acquisition and MindNet AI. Its main function would not be to replace artificial intelligence algorithms or perform all neural decoding, but to provide an already developed computational infrastructure used to receive, organize, preprocess, and analyze fMRI data during acquisition. In this way, Pyneal can act as a bridge between the physical domain of neuroimaging and the computational domain of MindNet.

MacInnes et al. (2020) developed Pyneal specifically as an open-source platform for real-time functional magnetic resonance imaging (rt-fMRI). Its architecture was designed to allow access to brain function during the examination itself, enabling data quality monitoring, real-time analysis, neurofeedback, dynamic control of experiments, and communication with external devices or computing systems.

The internal structure of Pyneal is particularly interesting for MindNet because it already separates the operation into functional components. The Pyneal Scanner monitors the new data produced by the acquisition system, transforms it into a standardized format, and sends each new three-dimensional volume to the Pyneal module. Pyneal itself has three main components: scan receiver, processing module, and results server. The first receives the volumes; the second performs the pre-processing and analysis operations; and the third makes the results available to other systems during the examination itself (MacInnes et al., 2020).

Each new volume received corresponds to a three-dimensional matrix of voxels associated with a specific moment in the acquisition. Pyneal uses transmitted information to correctly reconstruct the volume dimensions and position it temporally within a 4D structure that is progressively filled during the examination. The result of each analysis remains associated with the corresponding temporal index, an important aspect for MindNet because the comparison between sender and receiver depends not only on the content of the neural representations, but also on their temporal position.

Another particularly relevant feature is that Pyneal's Results Server uses a TCP/IP socket interface. An external system can request the result corresponding to a specific volume, and the server responds in JSON format.

MacInnes et al. (2020) refer to this external component as the “End User,” which can be any system authorized to use the results produced during acquisition. This concept can be extended to MindNet AI, which can occupy the position of a downstream system that continuously receives results from the rt-fMRI pipeline and incorporates them into neurodigital processing.

Thus, Pyneal provides a particularly interesting computational interface between neuroimaging and telecommunications, and Mindnet therefore does not need to perform advanced neural decoding on its own. The architecture itself is described by MacInnes et al. (2020)

It allows for customized analyses, making it possible to insert subsequent computational models or specific pipelines. At MindNet, the results produced by Pyneal can feed machine learning and deep learning algorithms designed for further noise reduction, feature extraction, pattern recognition, dimensionality reduction, neural decoding, and construction of the neurodigital representation.

Pyneal and MindNet AI are therefore not competing technologies; they can be layered. Pyneal handles the operational interface with rt-fMRI and the necessary real-time processing; MindNet AI adds specialized models capable of transforming this data into more complex neurodigital representations. This modularity is consistent with Pyneal's own design, which allows for customized scripts and analyses tailored to the needs of each experiment (MacInnes et al., 2020).

Pyneal can process volumes as they are produced, but “real-time” in rt-fMRI does not mean millisecond neuronal time. The system works within the temporal resolution of the acquisition and the hemodynamic response. Therefore, MindNet AI must consider timestamps, hemodynamic delay, processing time, network latency, receiver interaction, and reacquisition. Pyneal itself monitors the processing time of each volume, allowing verification that the analysis keeps pace with the acquisition speed (MacInnes et al., 2020). For chronic pain, however, the impact will be minimal, and the solution remains a solid one of the best options in a market where opioids are the main choice.

There is also an important distinction within the proposed multimodal architecture: Pyneal was developed specifically for rt-fMRI and should not be presented as an established pipeline for HP-^{13}C MRI. Metabolic information from HP-^{13}C should have its own acquisition and processing pipeline. It is later, in MindNet AI, that the characteristics derived from the different modalities can be integrated into a multimodal representation. However, this division strengthens the architecture because it assigns each technology a technically defined function. Pyneal constitutes the operational processing layer of real-time rt-fMRI; the HP-^{13}C pipeline provides the metabolic dimension; and MindNet AI performs multimodal integration, neural decoding, neurodigital representation, alignment, and sender-receiver comparison. The telecommunications component transports the resulting representation.

Thus, Pyneal's importance to MindNet lies not only in the fact that it is fMRI software. MacInnes et al. (2020) have already demonstrated an architecture in which acquisition, processing, analysis, TCP/IP, and the provision of results to external systems occur during the same session. MindNet extends this principle by placing MindNet AI and the telecommunications infrastructure within this interface, transforming the result of rt-fMRI processing into one of the inputs of a continuous neurodigital chain. Pyneal can therefore constitute one of the software bridges between real-time neuroimaging and the neurodigital telecommunications architecture proposed by MindNet.

Also, in the MindNet architecture, DICOM and Pyneal are complementary in the transition between physical acquisition by magnetic resonance and the construction of a representation.

Neurodigital by MindNet AI. DICOM provides a standardized language for representing, identifying, storing, and exchanging medical imaging data; Pyneal adds an operational layer capable of accessing and processing fMRI data during the acquisition itself. MindNet uses this combination as part of the bridge between neuroimaging, artificial intelligence, and telecommunications.

DICOM — Digital Imaging and Communications in Medicine — is an international standard for communication and management of medical image information and related data. In the MindNet architecture, this means that the information produced by neuroimaging equipment originates within a standardized digital structure, containing not only pixels or voxels, but also metadata necessary to identify the study, series, instance, modality, and acquisition parameters.

DICOM preserves the interoperable structure of neuroimaging information. Pyneal transforms the successive arrival of this data into a computational flow of rt-fMRI. MindNet AI, in turn, can receive results or representations derived from this processing to perform more advanced operations, such as additional denoising, for example, which is so important for obtaining neural states. And DICOM objects also remain as the source, record, and reference of the acquisition in DICOMweb. Koutelakis et al. (2018) describe DICOMweb as the extension of DICOM interoperability to web technologies, using web standards-based services to store, search, and retrieve medical image objects. The authors already pointed out that this architecture reduced barriers to image analytics and machine learning, precisely because computational applications could retrieve images and related data through standardized web interfaces.

In this design, DICOM functions as the interoperable language for neuroimaging, Pyneal as a bridge for real-time rt-fMRI processing, and MindNet AI as the layer that transforms relevant characteristics of this data into neurodigital representations intended for analysis, comparison, and transmission. The chain, therefore, ceases to be simply "MRI ÿ image" and assumes a continuous computational organization. It is important to emphasize that this information would be obtained and shared with the authorization and consent of the Sender and Receiver at each stage.

5.5 HP-^{13}C MRI on MindNet: nuclear metabolic reading, dynamic acquisition, and increased sensitivity.

HP-^{13}C MRI adds a dimension to the MindNet architecture that rt-fMRI BOLD, in isolation, does not provide: the possibility of directly monitoring metabolic transformations. While rt-fMRI uses hemodynamic and blood oxygenation changes as an indirect measure related to neural activity, HP-^{13}C MRI explores the magnetic properties of the ^{13}C nucleus and dynamically monitors the metabolic fate of hyperpolarized [1-^{13}C]pyruvate, lactate, and bicarbonate. Li, Vigneron, and Xu (2021) highlight precisely that HP-^{13}C MRI allows the acquisition of dynamic metabolic information in real time in the human brain, complementing anatomical and functional modalities.

The first important element is, therefore, the metabolic reading from the ^{13}C nucleus.
Carbon-13 has nuclear spin active in magnetic resonance, but its abundance

Natural sensitivity is small, and conventional sensitivity is low. Hyperpolarization radically modifies this condition. Techniques such as dissolution Dynamic Nuclear Polarization (dDNP) increase nuclear polarization before acquisition, raising the MR signal by several orders of magnitude. Khan and Laustsen (2025) describe polarization increases exceeding 10,000 times under certain conditions, while recent reviews report signal-to-noise ratio gains that can reach tens of thousands of...
times.

This property is particularly important for MindNet because it transforms metabolically relevant molecules into temporally much more detectable sources of physical information. The most developed example is hyperpolarized [1-^{13}C]pyruvate. After administration, pyruvate participates in metabolism, and the ^{13}C label can appear on metabolic products such as [1-^{13}C]lactate and ^{13}C-bicarbonate. The pyruvate-lactate conversion is related to lactate dehydrogenase and the metabolic state of the tissue, while bicarbonate formation is associated with the entry of pyruvate into oxidative metabolism via pyruvate dehydrogenase. Thus, HP-^{13}C MRI provides not only a static image but also allows monitoring the temporal behavior of the substrate and its metabolic products.

Park et al. (2018) demonstrated the feasibility of this approach in the human brain using hyperpolarized [1-^{13}C]pyruvate. Their work showed dynamic acquisition of pyruvate and metabolic products, including lactate and bicarbonate, establishing an important precedent for the use of HP-^{13}C as a metabolic component in human brain characterization. Subsequently, Li and Xu (2021) reviewed human brain applications and emphasized that the ability to obtain dynamic metabolic information is one of the fundamental characteristics of this technology.

The second important element for MindNet is precisely this temporal dimension.
In this context, "real-time" does not mean tracking each action potential on a millisecond scale. It means dynamically acquiring the evolution of metabolism during the relatively short window in which hyperpolarized magnetization remains available. Harris et al. (2018) demonstrated that HP-[1-^{13}C]pyruvate allows tracking brain metabolism on a second scale. However, there is a difference in time scales that needs to be considered by the algorithm. Action potentials and many synaptic events occur on millisecond scales, while the BOLD response evolves much more slowly. This difference appears directly in the work of Tang et al. (2023): the authors highlight that the slowness of the BOLD response constitutes a problem for continuous language decoding, because each brain image can reflect information corresponding to multiple words. The decoder then needs to computationally handle this temporal difference (Tang et al., 2023).

Therefore, "real time" does not mean that all physiological phenomena have the same latency. It means that the system operates continuously taking into account different temporal constants, acquisition times, processing, transmission, and physiological response. MindNet AI needs to perform this temporal correspondence, associating the acquired states of the sender with the subsequent responses of the receiver and incorporating these relationships into the next cycle of the closed loop.

For MindNet, this allows them to conceive of two complementary information channels:

rt-fMRI/BOLD ÿ dynamic functional, hemodynamic, and oxygenation information

HP-13C MRI ÿ dynamic metabolic information

The value for MindNet in this case lies precisely in the complementarity of this information. MindNet AI can receive features derived from both pipelines and integrate them into a multimodal representation of the brain state.

Furthermore, the increased sensitivity provided by hyperpolarization is especially interesting for the remote acquisition proposed from the existing telecommunications network. Hsieh et al. (2024) describe precisely the high sensitivity of HP MRI as a consequence of increased nuclear polarization, while Khan and Laustsen (2025) show that hyperpolarization allows the study of nuclei and molecules whose conventional sensitivity would be insufficient for various applications.

In the MindNet architecture, therefore, increased range should be formulated as a technological consequence of RF and also as a consequence of increased detectability. The precedent has already been set by the very significant increase in sensitivity; and this gain can be converted into range when associated with its distributed RF infrastructure, detection systems, and MindNet AI.

The issue of remote acquisition can be understood as a joint problem of physics and processing: available signal strength, noise, distance, detection geometry, receiver sensitivity, interference, spatial and temporal resolution, and computational capacity to identify the informational component. HP-^{13}C contributes by increasing physical detectability; MindNet AI contributes by seeking to extract, separate, and reconstruct information. AI can contribute significantly when weak signals are present in high-dimensionality and noisy environments. Hsieh et al. (2024) point to artificial intelligence as one of the future directions for improving analysis, reproducibility, and clinical applications of the modality. Khan and Laustsen (2025) also describe simultaneous advances in data acquisition and analysis, while the review “Quo Vadis Hyperpolarized ^{13}C MRI?” (2025) explicitly identifies artificial intelligence methods among the current lines of development in the area.

The HP-^{13}C MRI thus offers several particularly relevant contributions to MindNet, including the reading of metabolic processes through magnetically active ^{13}C nuclei; dynamic acquisition capable of tracking metabolic transformations in real time within its hyperpolarization window; and an increase in sensitivity of several orders of magnitude that enhances signal detectability, in addition to noise reduction. Park et al. (2018), Li and Xu (2021), Hsieh et al. (2024), and Khan and Laustsen (2025) provide a convergent technological basis for these first three elements.

In the MindNet architecture, ^{13}C hyperpolarization increases nuclear magnetization and MR signal detectability, providing a greater sensitivity margin to the system.

RF acquisition. MindNet AI becomes especially important as the distance increases. As the signal approaches the detection limit, processing algorithms can be used for noise reduction, interference identification, reconstruction, multimodal fusion, and feature extraction. The state-of-the-art HP MRI already treats acquisition and analysis as closely related parts: Khan and Laustsen (2026) highlight that maximizing the information obtained from a hyperpolarized sample requires joint optimization of acquisition and analysis, because there is a finite budget for hyperpolarized magnetization.

Therefore, AI and hyperpolarization can act in a complementary way. HP-^{13}C improves the initial physical condition of the problem by increasing the polarization and intensity of the signal; MindNet AI subsequently acts on the measurements obtained. If relevant brain information is present in the signal, even if mixed with noise and interference, computational techniques can increase the ability to identify it. Acquiring a much more detectable nuclear signal, combined with high-sensitivity receivers, distributed RF infrastructure, and advanced computational processing, allows for a progressive shift in the operational detection limit.

Thus, the contribution of HP-^{13}C to the achievement of MindNet can be presented as an engineering hypothesis directly derived from an already established principle: hyperpolarization increases nuclear polarization and MRI sensitivity by several orders of magnitude (Khan and Laustsen, 2026); HP-^{13}C allows for the dynamic retrieval of metabolic information in the human brain (Cunningham et al., 2019); remote NMR configurations demonstrate that detection components can be spatially rearranged (Ledbetter et al., 2008; Verpillat et al., 2008); and integrated RF systems demonstrate the coexistence of MR acquisition and wireless communication (Darnell et al., 2019).

The MindNet AI proposal therefore establishes a bridge between neuroscience and telecommunications engineering, transforming brain-to-brain communication into a problem of acquisition, transduction, representation, interoperability, encoding, transmission, reception, synchronization, control, and feedback. The central question ceases to be whether a brain field can directly traverse large distances and becomes how information derived from neural states can be transported, preserved, delivered, and verified through a distributed neurodigital infrastructure.

6. The silent epidemic of chronic pain

6.1 A global health challenge

In Brazil, the epidemiological dimension of chronic pain reinforces the need for the development of new strategies for prevention, treatment, and neuromodulation. A systematic review and meta-analysis published in 2023 estimated that 35.70% of the Brazilian adult population experiences chronic pain, while among the elderly the prevalence reaches 47.32%. In addition to the high frequency, approximately half of those affected reported disability associated with pain (Aguiar et al., 2023). These numbers demonstrate that chronic pain transcends the individual dimension and constitutes a significant public health problem in Brazil, with functional, social, and economic repercussions.

In the United States, the country where I became a naturalized citizen, more than 50 million American adults live with chronic pain, and approximately 17 million with high-impact chronic pain. In Europe, economic studies have also shown that the costs of conditions associated with chronic pain are equivalent to several percentage points of GDP in certain countries, including medical expenses, hospitalizations, sick leave, social benefits, and early retirement. The WHO projects approximately 843 million cases in 2050 and identifies low back pain as the leading cause of disability worldwide.

The high prevalence, persistence over time, and functional, social, and economic impact of chronic pain allow it to be characterized, in a broad epidemiological sense, as a problem of epidemic magnitude.

In this context, the development of MindNet as a neurodigital telecommunications architecture, intended, among its possible applications, for the investigation of new strategies for modulating chronic pain, addresses a clinical need that affects a significant portion of the world's population.

The economic dimension of chronic pain allows us to estimate the potential magnitude of the economic impact of technologies capable of measurably reducing pain-related disability. In a purely illustrative scenario where a technology like MindNet reached 10% of the population economically affected by pain and reduced associated costs in that group by 25%, the application of US values would correspond to approximately US$14–15.9 billion annually in potentially avoided costs. In a larger-scale scenario, with 50% coverage and a 50% reduction in the economic burden among treated individuals, this value could reach approximately US$140–158.8 billion annually. These projections demonstrate the potential economic scale of an intervention that produces clinically proven reductions in pain, disability, and global productivity losses.

In this model, the reduction of pain and disability could decrease hospitalizations, consultations, treatments, absences from work, and other costs associated with the disease; functional recovery could increase working hours and reduce absenteeism; and the implementation of the architecture itself could establish a new neurodigital economic chain.

Furthermore, prolonged pharmacological treatment of chronic pain can also generate adverse effects, the need for monitoring, and additional costs for healthcare systems. Some classes of medications present significant risks when used for prolonged periods or in vulnerable populations. In the author's case, after approximately six years of treatment, renal and brain morphological changes were identified, in a context where the medications used did not provide complete pain control. Non-steroidal anti-inflammatory drugs, for example, are associated with gastrointestinal, cardiovascular, and renal risks, while other medications used in the treatment of chronic pain can produce sedation, dizziness, and cognitive effects (CDC, 2022).

Regarding opioids, although they are essential medications in certain clinical situations, their prolonged use for chronic pain presents an imminent danger to many patients and is associated with risks of opioid use disorder, overdose, and other serious adverse events.

In the United States, millions of people report misuse of prescription opioids or a disorder related to their use, while hundreds of thousands of overdose deaths involving prescription opioids have been recorded over the past few decades.
This problem adds to the economic burden of pain costs related to addiction treatment, emergency care, hospitalizations, lost productivity, and premature mortality.

In this context, MindNet proves to be a necessary option, capable of reducing pain intensity, disability, and the need for pharmacological treatment. Its potential economic impact may include reducing prolonged exposure to certain medications and costs associated with their adverse effects. The safe reduction in the need for opioids may bring additional benefits related to less exposure to prescribed opioids and, consequently, a reduction in the risks associated with their prolonged use, including opioid use disorder and overdose.

7. Conclusion and implementation perspectives of MindNet

7.1 Uniting Science, Health and the Future

MindNet can be implemented progressively and modularly, starting from components that already have precedents and are even in use at this moment, and advancing towards their integration into a closed-loop neurodigital system. As the inventor, I hope that this implementation will be as simple as "restarting" a system after a bug, and starting by integrating existing technologies in a coordinated way to make them operate in unison within a new architecture guided by the principle of primum non nocere — "do no harm". The development of an alternative for the relief of chronic pain can advance as soon as the necessary resources, and the justice system, are available.

As a medical student, I envision targeted and controlled studies being conducted in educational and research institutions, and MindNet, in the future, connecting people with the purpose of contributing to the pain relief of millions. As an activist (@ju4justice), I would like to bring the issue of chronic pain, in its enormous public health dimension, to spaces where science, public policy, and legislation can converge in the discussion of solutions with global reach, including international organizations that support democracy, such as the United Nations (UN) and the World Health Organization (WHO). As a mother, I wish for healing for my family.

The most rational approach is this one. After building a sequence of proof-of-concept projects based on the studies presented here, each stage of the architecture can be evaluated objectively, measurably, and reproducibly. As these proofs are demonstrated, the discussion will progressively move from the realm of theoretical feasibility to that of execution—and I have more than ten years of experience implementing telecommunications solutions. At this stage, any objections to...

The implementation of MindNet will need to be confronted not only with the results produced by the proof-of-concept itself, but also with the body of scientific literature cited in this work, which provides independent precedents for various components of the architecture. It is precisely a transparent sequence of proof-of-concept tests that will allow data—and not personal opinions—to determine how far the integration proposed by MindNet can go. The scientific question, therefore, should not be who is for or against MindNet, but what functions can be demonstrated and what problems this technology can help us address, especially considering the human and social dimension of chronic pain.

In short, MindNet can be understood as a neurodigital telecommunications architecture in which the brain simultaneously constitutes a source and a destination of information. So, let's open ours. Its fundamental logic follows the historical evolution of telecommunications: phenomena that were originally not transmissible over long distances in their physical form are acquired by transducers, converted into representations, encoded, transported by networks, and reconstructed or used at the receiving end. And, with each implementation, the economy follows the advance—something especially significant for those who, like me, believe in the value of honest work as a force for economic and social development.

A voice doesn't travel through an optical fiber like sound. A photograph doesn't travel across the internet like light. A video doesn't travel across a network like physical movement. In the same way, in MindNet, the neural state doesn't need to travel distance like a brain field.
It is acquired, converted into data, and transformed into a transmissible neurodigital representation. It is this shift in domain—from neural to physical, from physical to digital, and from digital to telecommunications—that allows us to conceive of distance not as an absolute barrier, but as an invitation to *connection.*

8. The personal origin of MindNet 8.1 My journey so far

Upon becoming disabled during childbirth, I began to use a wheelchair or crutches to get around, and my own body became, in a way, an object of study for me. From the experience of living with chronic pain for six years, I discovered how to adapt to and cope with this condition which, in some cases—and particularly in mine—can even resemble a form of torture, due to its intensity and persistence.

My son and I are still waiting for the courts to enforce our right to restitutio in integrum, the legal principle of full reparation, which seeks to restore, as far as possible, the situation that would have existed had the damage not occurred, through full compensation for the losses suffered. With resources limited by the situation described above, while awaiting the corresponding compensation for the damages suffered, I have begun the treatments that are financially available to me, even though these present risks and side effects, and do not necessarily provide a full recovery.

(CGC-23-11182, CGC-25-622102)

After developing fibromyalgia as a consequence of a spinal injury, I set myself the goal of finding an alternative. Therefore, this study was born, like a lotus flower in the mud, from a great personal need and, at the same time, from a problem of global scope.

It was because of fibromyalgia that I understood that, to study pain, I needed to better understand the brain. That's where my interest in neuroscience began. And, since I couldn't leave my own trajectory behind, my technical background in telecommunications and computer science naturally brought technology into this investigation, and from there, everything is history.

This study, therefore, also arises from the need to establish a technically defined bridge between fields that have traditionally been investigated relatively independently in the fight against chronic pain: the neuroscience of neural transduction and representation processes and telecommunications engineering, which is responsible for transmitting information over long distances.

This convergence of areas that were part of different moments in my career ended up becoming the interdisciplinary basis for thinking about an architecture in which neural states could be synchronized between individuals.

It was from this encounter between my personal experience, neuroscience, and technology that the MindNet proposal emerged, the subject of patent applications before the INPI (Brazilian National Institute of Industrial Property) and the USPTO (University of the State of Tocantins), and which uses different technologies in unison to investigate the possibility of assisting the brain in one of the tasks that have become central to my research: modulating pain through the synchronization of neural states.

Restitutio in integrum doesn't just represent the possibility of rebuilding everything my family has lost in the last six years—after all, how could anyone possibly replace six years of someone's life? For me, it also represents the opportunity to implement MindNet, hoping to overcome chronic pain and reclaim the life it prevents me from living; and for my son, it means something no economic value could measure: the possibility of having his mother back.

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Important note for the text: where you wrote “(Aguiar et al., 2023)” for the Brazilian prevalence of 35.70%, it should read “(Santiago et al., 2023)”. The study found 35.70% in the adult population and 47.32% among the elderly.

אֵל נָא רְפָא נָא לָהּ (El na, refa na lah)

Book of Numbers, chapter 12, verse 13.
This is the shortest prayer in the Bible:
"Oh God, please heal her now."