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Neuroimaging and Analyzing Brain Matrices

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A B S T R A C T

This paper explores various neuroimaging techniques for analyzing brain activity and understanding brain structures and functions. Techniques like Electroencephalography (EEG), Magnetoencephalography (MEG), functional Magnetic Resonance Imaging (fMRI), Computed Tomography (CT), Positron Emission Tomography (PET), and Near-Infrared Spectroscopy (NIRS) are examined, highlighting their advantages and limitations. We introduce an innovative approach using Magneto-Impedance (MI) sensors for real-time brain activity monitoring, specifically targeting the alpha rhythm and Event-Related Field (ERF) P300. This method offers a more portable and practical alternative to traditional MEG systems based on superconducting Quantum Interference Devices (SQUIDs). Additionally, we discuss developing "mind-reading" devices that capture high-frequency broadband (HFB) responses to cognitive tasks.

1. INTRODUCTION

There are various methods to gather information about brain structures and functions, each with its own advantages [1]. Some techniques are safer, while others may be more complex or expensive. Despite their differences, all these methods provide invaluable data on brain activity, helping to diagnose conditions and diseases that might otherwise remain undetected. Let's explore the methods available in modern medicine for brain scanning [2]. The three most widely used techniques are Electroencephalography (EEG), Magnetoencephalography (MEG), and functional Magnetic Resonance Imaging (fMRI) [3-5].

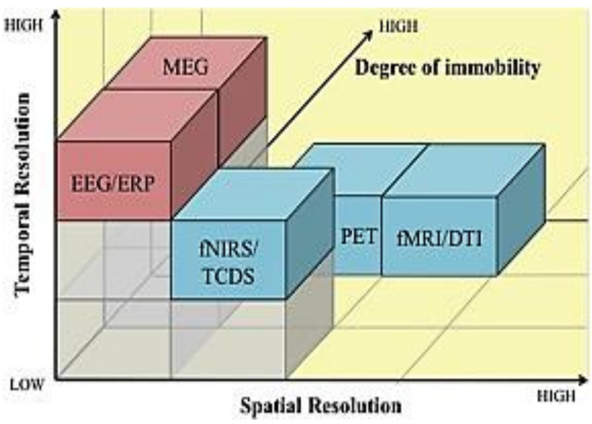

Fig. 1. Frequently used devices for measuring brain activity.

Among these, EEG stands out for its versatility and cost-effectiveness. Common devices for measuring brain activity are illustrated in Figure 1.

2. BRAINWAVE MAPPING

Brainwave mapping involves visualizing brain activity patterns by recording electrical signals from different regions, helping to understand cognitive functions and neural responses.

2.1 Electroencephalography (EEG)

Electroencephalography (EEG) allows the neuro-scientists and researchers to explore brain activity by capturing the electrical signals produced across different cortical layers. These signals originate from the densely packed pyramidal cells in the brain's gray matter, which communicate in synchronized patterns [6]. As these cells fire together, the electrical impulses travel to the scalp, where they are detected by EEG electrodes. Due to their faint nature, these signals are amplified to ensure clarity. A reference measurement is taken from a location behind the ears, known as the "mastoid processes," to provide a baseline for comparison. EEG excels in temporal resolution, capturing brain activity with precision up to 1 millisecond, depending on the sampling rate. This allows for the detection of brain responses shortly after visual or auditory stimuli and enables monitoring of brain states such as engagement, motivation, and drowsiness over extended periods [7, 8]. This exceptional time resolution offers detailed insights into the precise timing of brain processes.

2.2 MEG (Magnetoencephalography)

Magnetoencephalography (MEG) differs fundamentally from EEG in its method of data collection. While EEG measures electrical activity generated by neural firing, MEG detects the magnetic fields produced by this activity. MEG devices are stationary, similar to fMRI systems, requiring participants to remain still with their heads fixed inside a shielded chamber to prevent external magnetic interference [9]. MEG offers the unique advantage of combining the high temporal resolution of EEG with the spatial precision of fMRI. This integration provides a detailed understanding of both the timing and location of brain activity, enabling precise mapping of active brain regions and a comprehensive view of the brain's structure.

2.3 Functional Magnetic Resonance Imaging (fMRI)

Functional Magnetic Resonance Imaging (fMRI) is a neuroimaging technique that measures brain activity by detecting changes in blood flow associated with neural activity [10]. The principle behind fMRI is that active neurons require more oxygen, resulting in increased blood flow to those areas. Although fMRI has lower temporal resolution due to the slower speed of blood flow, it excels in spatial resolution, allowing for intricate mapping of brain structures. During an fMRI scan, participants lie still inside a magnetic core while superconducting magnets rotate rapidly around them [11]. fMRI detects variations in magnetization between oxygen-rich and oxygen-poor blood, revealing relative activity across different brain regions. This technique can generate highly detailed images of brain structures and accurately reconstruct individual skull shapes and cortical layers.

2.4 Computed Tomography (CT)

Computed Tomography (CT) scanning provides a visual representation of the brain based on differential X-ray absorption. During the scan, the patient lies on a table that slides into a cylindrical machine. X-rays pass through the head and are detected by the machine, which captures the varying absorption levels of the X-ray beam by different tissues. Bone and hard tissues absorb X-rays well, while air and water absorb less, with soft tissues falling in between.

CT scans effectively show the gross features of the brain but lack detailed structural resolution. Because CT scans are akin to X-ray images, they involve a small amount of radiation and are not suitable for frequent use.

2.5 Positron Emission Tomography (PET)

Positron Emission Tomography (PET) measures brain activity by tracking glucose levels, as active neurons use glucose as an energy source. A tracer substance attached to radioactive isotopes is injected into the bloodstream, where it travels to active brain regions, providing visible spots of activity. These spots are detected and displayed as a video image of the brain performing specific tasks. While PET offers insights into general areas of brain activity, it does not pinpoint specific locations. Additionally, PET scans are costly and invasive, limiting their practical use. However, they can be successfully used in some forms of medical diagnosis, including for Alzheimer's. Working principle of the PET scan is shown in Figure 2 while some of the images obtained by applying the same technique is presented in Figure 3.

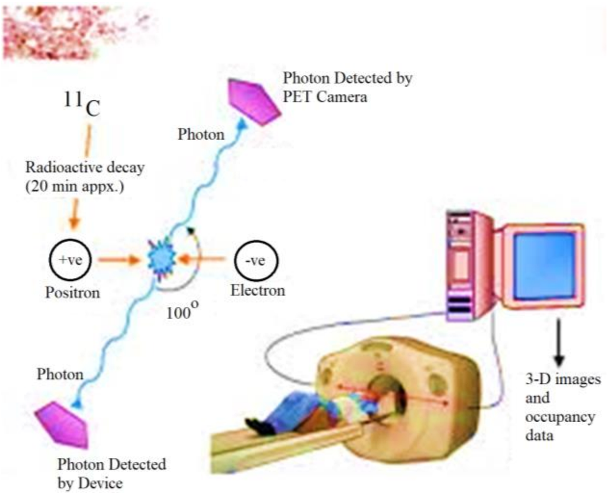

Fig. 2. Working principle of the PET scan.

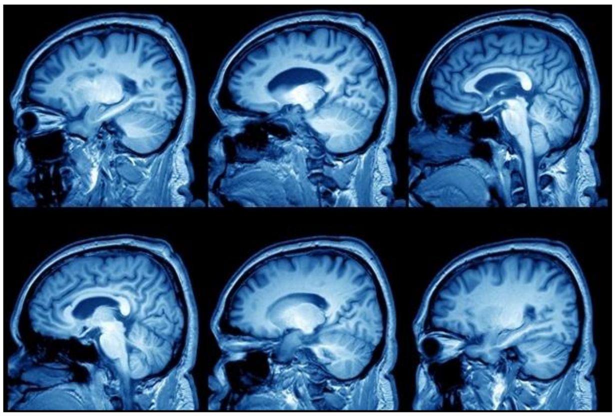

Fig. 3. Images of the PET scan.

2.6 Near Infrared Spectroscopy (NRS)

Near Infrared Spectroscopy (NIRS) is a non-invasive optical technique used to measure brain activity by evaluating changes in blood oxygenation. This method employs a beam of near-infrared light (ranging from 700 nm to 900 nm) that penetrates the skull and measures the attenuation of the light as it exits. Variations in blood oxygenation affect the degree of light attenuation, allowing for an indirect assessment of brain activity. While NIRS may not offer the highest accuracy or the most detailed information compared to other techniques, its primary advantage lies in its safety and simplicity. NIRS is gentle for patients, making it an ideal choice for situations where minimal discomfort is essential. Figure 4 illustrates the near-infrared spectrum, and Figure 5 outlines the procedural steps for implementing this technique.

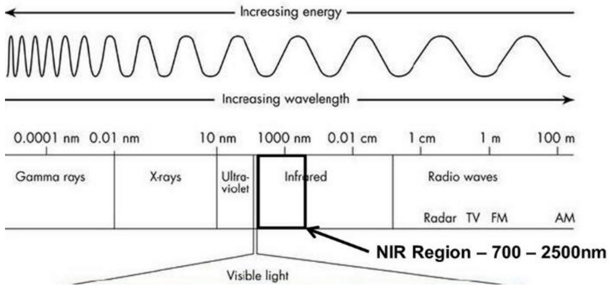

Fig. 4. NIR in the electromagnetic spectrum.

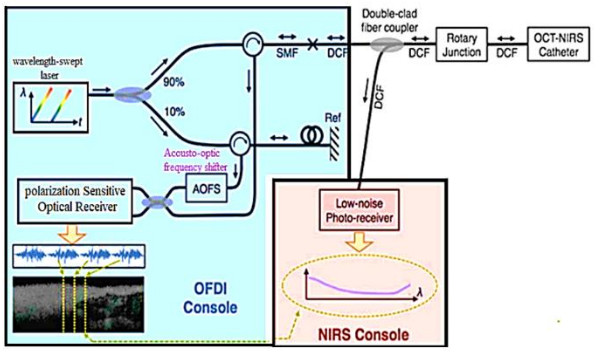

Fig. 5. Different steps for implementing the NIRS technique.

2.7 Brain Activity Measurement using MI Sensor

Advances in brain research over the last three decades have significantly deepened our understanding of neural functions. In medical and healthcare fields, analysing brain signals aids in diagnosing conditions like epilepsy and neural damage. Brain-Computer Interface (BCI) technology, which relies on real-time brain signal processing, has revolutionized neuroprosthetics, enabling neural repair and rehabilitation and even substituting non-functional limbs for individuals with disabilities. By measuring and analysing brain activity in real-time, we can harness invaluable insights for various applications, including driver drowsiness detection and interactive video games. Superconducting Quantum Interference Devices (SQUIDs) are the most widely used sensors for detecting the brain's weak magnetic fields. However, their need for extremely low temperatures to maintain superconductivity makes them bulky and inconvenient. To address this, scientists have developed a measurement system based on highly sensitive Magneto-Impedance (MI) sensors, which can operate in normal environments. These sensors effectively monitor brain activity, particularly the alpha rhythm in the occipital region and the Event-Related Field (ERF) P300 in the frontal, parietal, and temporal regions. The human brain's complex and weak electrical activity generates changes in the brain's magnetic field, measurable through Magnetoencephalography (MEG). While SQUIDs are the gold standard for MEG due to their high sensitivity and accuracy, their requirement for cooling makes them impractical for some applications. In contrast, MI sensors do not require cooling and are largely based on CMOS IC technology, offering a simpler structure and lower power consumption. The alpha rhythm, with an 8-13 Hz frequency range, is easily detectable at maximum amplitude over the occipital region. It is prominent during relaxed wakefulness with closed eyes and attenuates when the eyes open. This characteristic makes it useful for drowsiness detection in drivers and monitoring wakefulness levels. The alpha rhythm's large amplitude also influences other brain activity measurements, such as the ERF P300. ERFs are brain responses time-locked to events like sensory stimuli or target recognition, directly reflecting specific sensory, cognitive, or motor events. The P300 component, a positive deflection occurring 250-500 m/s after a stimulus, is crucial for applications such as brain injury inspection, neocortical epilepsy diagnosis, and the P300 speller.

2.7.1 Measurement System

Figure 6 exhibits the schematic diagram of the measurement system. The MI sensor is a micro magnetic sensor with high sensitivity (pico-Tesla resolution). The magnetometer is based on pulse-current magneto-impedance effect that originated from the skin effect in FeCoSiB amorphous alloy wires. For measuring the extremely weak magnetic field, inside the sensor head, two MI elements are set up in series. Each element includes four wires in a pickup coil to reduce magnetic noises. As shown in the figure, the measurement element can be used to determine the total magnetic field, including biomagnetic field and environmental magnetic noise. The reference element may be set up 3 cm behind to cancel out environmental magnetic noise like geomagnetic field. Voltage difference between the two MI elements is used as the output. It is an efficient technique for reducing the geomagnetic field noise. In order to make the device more flexible and wearable, the sensor-head is fixed into a head-wear polystyrene box connected with an extended shield cable. A schematic diagram of the measurement system and the structure of MI sensor head are shown in Figure 6.

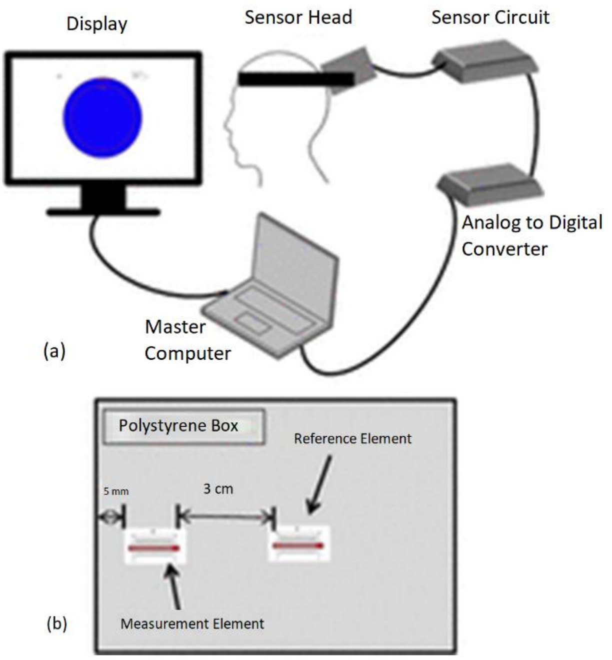

Fig. 6. Schematic diagram of the measurement system and the structure of MI sensor head.

The sensor output signals are amplified and a 24-bits ADC is used to convert the output signal into a digital signal which are then sampled with a 1000 Hz rate and filtered in a frequency band of 0.1-40 Hz to reduce the high frequency components. Figure 7 shows the noise spectral density of MI measurement system.

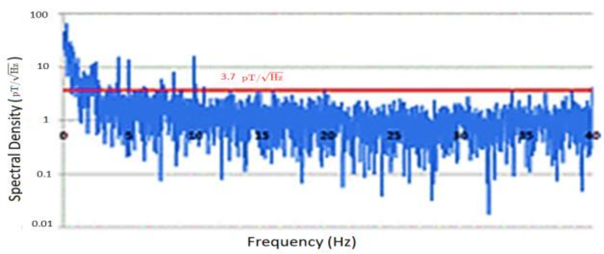

Fig. 7. Noise spectral density of the measurement system based on MI sensor.

2.7.2 P300 Measurement

To measure the P300, individuals undergo the oddball paradigm. In this task, they are presented with two types of visual stimuli in a random sequence every 800 milliseconds on a screen before them. When a target stimulus appears, they are instructed to press a response button as quickly as possible, while no response is required for a standard stimulus. To minimize the influence of the alpha rhythm, sensor heads are placed on the frontal, parietal, and temporal regions, and individuals are asked to keep their eyes open. In the case of P300 data processing, a band pass filter in the 1-9 Hz frequency range is applied, followed by a range filter to eliminate data affected by excessive movement [11]. The data is then categorized into standard and target conditions, and 100 instances of each condition are selected for arithmetic averaging using the same method. The flowchart for the real-time data processing module is presented in Figure 8.

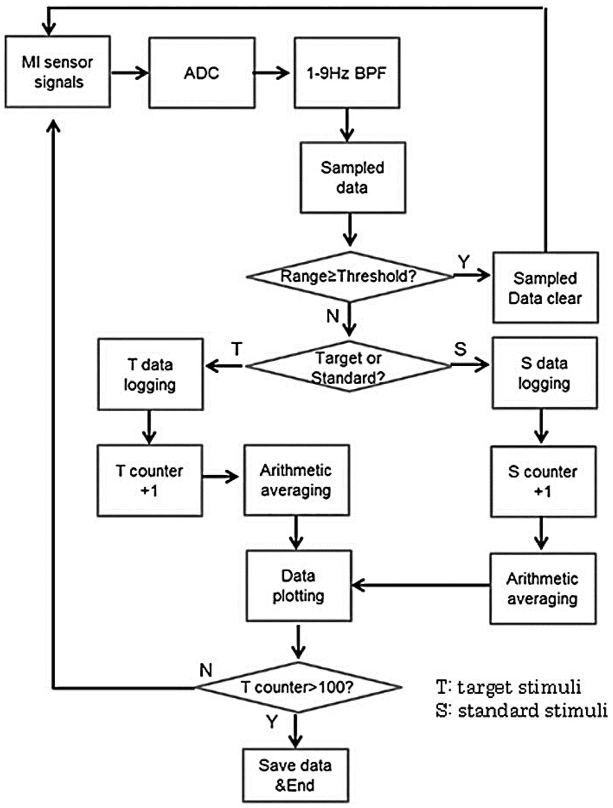

Fig. 8. Live-time signal analysis chart

2.7.3 Filtered Sensor Signals and Spectral Density

Figure 9 illustrates a segment of the filtered sensor signals (3 seconds) in both eyes-closed and eyes-open situations. Figure 10 (a) and (b) display the spectral density and the sum power spectrum level of the measurements. The results indicate that when the person opens their eyes, the signal amplitude decreases, and the sum power spectrum at every Hz level within the 8-13 Hz frequency band is noticeably reduced compared to when their eyes are closed, particularly around 10 Hz. This reduction in amplitude and power spectrum is consistent with the suppression of alpha waves typically observed when visual input is present. Alpha waves, primarily in the 8-13 Hz range, are more pronounced during relaxed, wakeful states with closed eyes and are reduced with increased sensory processing when the eyes are open. These findings support the idea that alpha wave activity is inversely related to visual and cognitive engagement, highlighting the dynamic changes in brain rhythms based on sensory states.

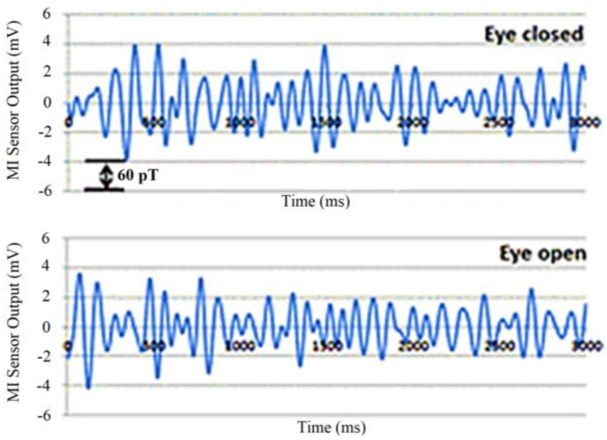

Fig. 9. Filtered sensor signals in both eyes closed and open situations.

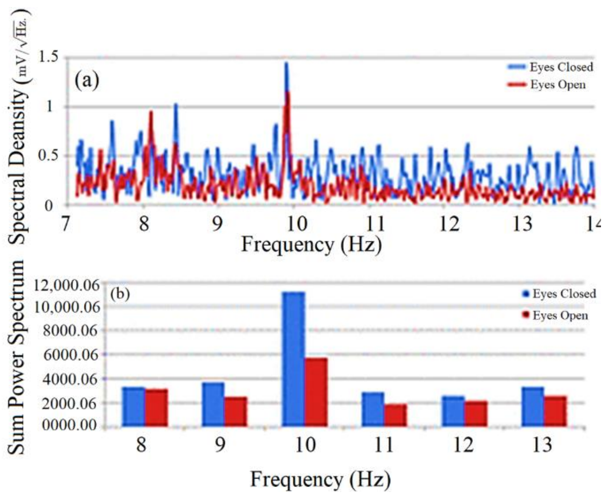

Fig. 10. Spectral density and the sum power spectrum level of all measurement.

2.8 "Mind-Reading" Devices, a New Method of Measuring Brain Activity

The experimental task Figure 11(a) consisted of self-paced arithmetic and non-arithmetic conditions. During the arithmetic condition, one can find a significant increase of activity in some but not all electrodes. As seen in the time-frequency plot (b), this activity is measured in the high-frequency broadband (HFB, 70–110 Hz) range. The temporal profile of relative HFB power changes (c) is shown for one representative electrode (P1–1) averaged across trials. Using d′-values, the separation of the distributions of HFB responses during arithmetic (red, target) and non-arithmetic (blue, non-target) conditions (d) could be quantified. In each participant's brain, the d′-values were mapped (e), and the sites with the highest d′-values (red) were located around the IPS region (white line in f). The IPS divides the superior (SPL) from the inferior parietal (IPL) lobules. PCS (post central sulcus) is shown with dashed line. Among all subjects, electrode P1–1 (red electrode with white circle in e) had the highest d′-value.

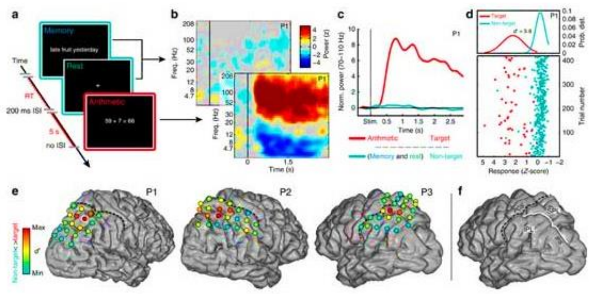

Fig. 11. "Mind-Reading" Devices simulation results.

3. CONCLUSION

Using a novel method, it has been collected the first solid evidence that the pattern of brain activity found in someone performing a mathematical exercise under experimentally controlled conditions is nearly equal to that observed when the person engages in quantitative thought in the course of daily life [12, 13]. The finding could lead to "mind-reading" applications which would allow a patient who is rendered mute by a stroke to communicate through passive thinking. It could also lead to more dystopian outcomes, chip implants that spy on or even control people's thoughts. Scientists have monitored electrical activity in a region of the brain called the intraparietal sulcus, known to be important in attention and eye and hand motion. Previous studies have hinted that some nerve-cell clusters in this area are also involved in numerosity, the mathematical equivalent of literacy. However, the techniques that previous studies have used, such as functional magnetic resonance imaging, are limited in their ability to study brain activity in real-life settings and to pinpoint the precise timing of nerve cells' firing patterns. These studies have focused on testing just one specific function in one specific brain region, and have tried to eliminate or otherwise account for every possible confounding factor. Procedure involves temporarily removing a portion of a patient's skull and positioning packets of electrodes against the exposed brain surface. Up to a week, patients remain hooked up to the monitoring apparatus while the electrodes pick up electrical activity within the brain. This monitoring continues uninterrupted for patients' hospital stay, capturing their inevitable repeated seizures and enabling neurologists to find the exact spot in each patient's brain where the seizures are originating. The electrodes implanted in patients' heads are like wiretaps, each eavesdropping on a population of several hundred thousand nerve cells and reporting back to a computer.

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