DRY EEG AND FNIRS SIGNAL ANALYSIS IN THE FREQUENCY DOMAIN: CASE OF STUDY OF PAIN DETECTION WITH WEARABLES DEVICES

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Ainhoa Osa-Sanchez
eVida Research Group, University of Deusto, Avda/Universidades 24, 48007 Bilbao, Spain.

Amaia Mendez-Zorrilla
eVida Research Group, University of Deusto, Avda/Universidades 24, 48007 Bilbao, Spain.

Begonya Garcia-Zapirain
eVida Research Group, University of Deusto, Avda/Universidades 24, 48007 Bilbao, Spain.

ABSTRACT: This study explores pain detection and analysis using wearable dry electroencephalography and functional near-infrared spectroscopy. Pain differs greatly from person to person and is affected by social, psychological, and biological variables. New advances in neurophysiological monitoring present encouraging opportunities to assess pain reactions in real time. We investigated neural and hemodynamic reactions to painful stimuli in the frequency domain using a combination of open-access datasets and real-time EEG and fNIRS data. Our findings demonstrate significant increases in theta, alpha, and beta frequency bands following pain administration, highlighting the brain's dynamic reaction to pain. In addition to improving our understanding of pain mechanisms, the integration of different modalities opens the door to new methods of clinical pain assessment and treatment. The portability and noninvasiveness of these technologies underscore their potential for broad use in therapeutic and research settings, especially when targeting frequency-specific pain responses.
KEYWORDS: EEG, fNIRS, Pain, Wearable, Frequency

INTRODUCTION

Pain is a complex and aversive sensory and emotional experience typically caused by actual or potential tissue damage, as defined by the International Association for the Study of Pain (IASP)[1]. The feeling of pain varies significantly between individuals, as it is inherently subjective and influenced by an interplay of biological, psychological, and social factors. People learn to conceptualize pain throughout their lives, and its expression

extends beyond verbal descriptions. Importantly, the inability to communicate does not prevent the possibility of experiencing pain, whether in humans or non-human animals.

Recent advancements have explored the use of neurophysiological signals, such as those obtained from electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS), for objective pain detection and classification. These modalities offer the potential for real-time, non-invasive monitoring of neural and hemodynamic responses under painful conditions [2].

Zolezzi et al. [3] investigated both linear and nonlinear approaches to detect and classify pain severity in individuals with neuropathic pain. Their study recruited thirty-six patients with neuropathic pain and used an EEG system with 22 channels to record brain activity. To set up a control database, thirteen healthy participants without neuropathic pain were also included. The study revealed that nonlinear EEG analysis, specifically using approximate entropy, effectively characterized pain states. This finding underscores the utility of nonlinear dynamics in differentiating between pain severities.

Xiao-yi Wang et al. [4] explored the application of functional near-infrared spectroscopy (fNIRS) to differentiate between healthy individuals and patients with knee osteoarthritis (KOA). The study comprised two stages:

1. Comparative Analysis: Differences in brain activation between healthy individuals and KOA patients were assessed.

2. Therapeutic Impact Assessment: Seventy-two KOA patients were categorized into two groups based on their treatment modality—medication alone or a combination of medication and ten physiotherapy sessions.

Eleonora Gentile et al. [5] tested the use of fNIRS with people with fibromyalgia patients the analgesic effect of motor zone activation. These patients suffer from a condition characterized by widespread musculoskeletal pain where simple movement can worsen their symptoms. They showed the participants videos that showed movements, and it was verified that the observation of the movement provokes activations and modulations of motor networks, which suggests cortical adaptation mechanisms capable of restarting a virtuous phase of beneficial interaction with the circuits related to pain.

The results proved that fNIRS effectively captured changes in brain activation associated with pain. Furthermore, the device's portability, wireless operation, and lightweight design make it a promising tool for pain assessment in clinical and research settings. The study concluded that fNIRS could serve as an objective index for evaluating both pain consistency and therapeutic efficacy in patients.

MATHERIALS

The acquisition of some physiological signals for test was conducted while participants performed a series of predefined exercises under the simultaneous application of painful

stimuli. Two portable, non-invasive devices were used to capture neural and hemodynamic responses during these sessions.

- **Electroencephalography (EEG):** Brain activity was recorded using the CGX Quick-32r EEG helmet. This device features 32 dry electrodes, positioned according to the 10-20 international system, ensuring standardized spatial resolution. The dry electrode technology dropped the need for conductive gels, facilitating faster setup times and reducing participant discomfort. The device works at a sampling rate of 500 Hz, providing high temporal resolution suitable for capturing dynamic brain activity during movement and stimulus exposure. Bluetooth connectivity enabled wireless data transmission, allowing participants to move freely during the experiment [6]. The type of dry EEG electrode also measures the brain's electrical activity [7]. In this case the electrode for measuring it is used electrode without gel, dry electrode. As an alternative solution for stable long-term EEG recordings. This type does not require laborious scalp preparation and are less time consuming [8].
- **Functional Near-Infrared Spectroscopy (fNIRS):** Hemodynamic changes were monitored using the NIRSport2 [9], a portable and lightweight device equipped with 8 sources and 8 detectors, forming up to 20 channels for cortical coverage. The device works at a sampling rate of 10 Hz and uses dual wavelengths (760 nm and 850 nm) to differentiate between oxygenated (HbO) and deoxygenated hemoglobin (HbR). Source-detector distances were optimized for cortical measurements (approximately 30 mm), and the system's Bluetooth functionality allowed real-time monitoring of hemodynamic responses without restricting movement.

INTEGRATION WITH OPEN ACCESS DATA

In conjunction with the EEG device, we used an open-access database of EEG signals related to pain stimuli, published by Tiemann et al [10]. This dataset, collected from 74 participants, provides valuable information on how the brain responds to pain at both individual and group levels. The data includes various EEG recordings captured during controlled painful stimuli, providing a benchmark for understanding neural patterns in pain processing.

The combination of real-time data captured with the EEG system and historical datasets enables deeper insights into the consistency and variability of neural responses to pain, contributing to the understanding of pain mechanisms at both local and global levels.

Also, we used an open-access database of fNIRS signals, which provides hemodynamic data related to pain stimuli [11]. This database includes measurements of hemoglobin concentrations from participants exposed to various painful stimuli, allowing researchers to explore the relationship between brain activity and pain processing in different populations.

This also opens opportunities for benchmarking algorithms and exploring trends in hemodynamic responses to pain. The use of these databases, alongside real-time data collection with the NIRSport2, creates a rich, multi-dimensional data set that supports more comprehensive research into pain mechanisms.

TIME-FREQUENCY ANALYSIS PROCEDURE

Figure 1. Analysis methodology

To conduct the time-frequency analysis, the procedure illustrated in Figure 3 was implemented with Python programming language. The analysis leveraged specialized libraries, including MNE-Python [12] for data processing. The process involved the following key steps:

1. Data Loading: Raw signal data was loaded into the analysis environment using Python libraries such as MNE-Python [12] and pandas/numpy for data handling and preparation.

2. Preprocessing: Signals were cleaned to remove artifacts, including eye movements, involuntary muscle activity, and noise. MNE-Python's preprocessing tools, such as ICA (Independent Component Analysis), were used to detect and remove eye movement artifacts. Time segments with sudden movements detected via an accelerometer were averaged and corrected to ensure data quality.

3. Event Extraction: Pain-related events were found and saved, marking the temporal points of stimulus application. These markers were extracted and stored using MNE-Python's event-handling utilities.

4. Epoch Generation: Based on the event markers, epochs were generated to define time windows of interest. This segmentation enabled focused analysis of neural and hemodynamic responses, leveraging MNE's epoching functions for EEG and compatible tools for fNIRS.

5. Time-Frequency Filtering: Frequency-specific filters were applied using MNE-Python's time-frequency analysis module (e.g., Morlet wavelet transforms or multitaper spectral estimation) to isolate relevant frequency bands, tailored to the characteristics of the signals.

By combining MNE-Python for EEG analysis and tools like the nirs-toolbox or custom scripts for fNIRS, this workflow provided a robust foundation for extracting meaningful time-frequency features associated with pain-related brain activity.

RESULTS

In this approach, the decomposition of the EEG signal into its part frequency bands is essential, as each band exhibits unique functional characteristics. The typical frequency bands, along with their approximate spectral boundaries, are as follows:

- Delta (1–3 Hz): This band is often associated with deep sleep and certain brainwave activities in infants.
- Theta (4–7 Hz): Commonly linked to drowsiness, light sleep, and creativity.
- Alpha (8–12 Hz): Generally observed in relaxed, calm, and meditative states.
- Beta (13–30 Hz): Associated with active thinking, focus, and problem-solving.
- Gamma (30–80 Hz): Tied to higher mental activity, including perception and consciousness.

For the fNIRS signal, which measures hemodynamic responses, the crucial information is found within the 1–3 Hz frequency band. This band captures the oscillations related to blood oxygenation and deoxygenation, essential for understanding brain activity in response to various stimuli.

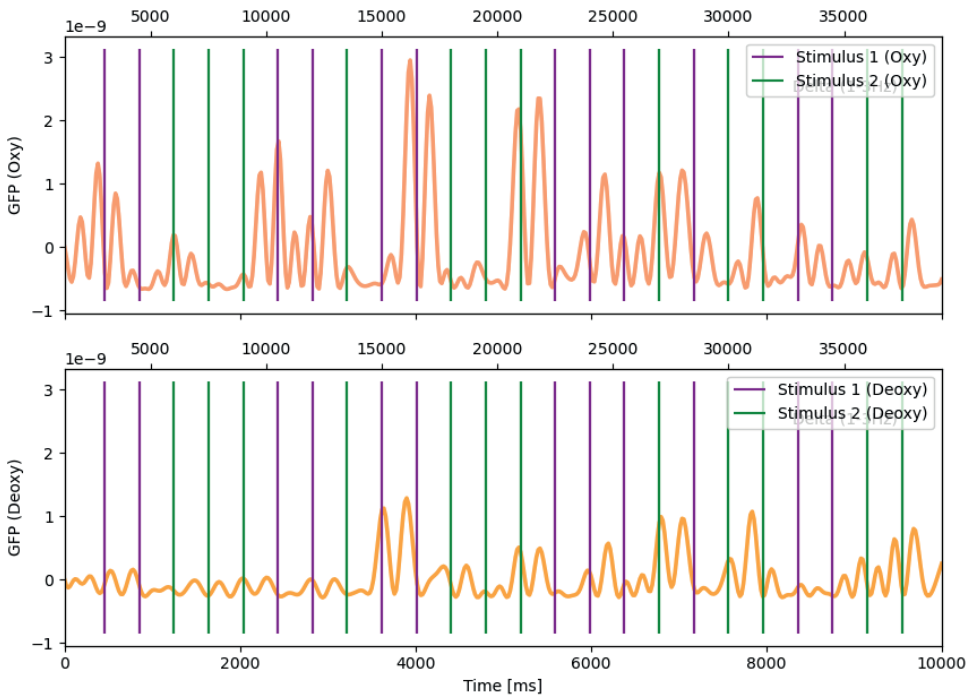

Figure 2. fNIRS time series

In reaction to painful stimuli, both signals have a distinctive hemodynamic response. This is shown by a rise in deoxyhemoglobin levels after a first increase in oxyhemoglobin

concentration. This kind of reaction is common in neuronal activity, where higher brain activity results in higher oxygen consumption, which in turn causes blood flow to increase to replace the oxygen that has been consumed. There are minor variations in the intensity and form of the reaction between the two painful stimuli, even though both signals exhibit a comparable hemodynamic response. These differences imply that different patterns of brain activation may be induced by different stimuli. Both oxyhemoglobin and deoxyhemoglobin signals clearly rise within the relevant frequency region when a painful stimulus is applied, as seen in Figure 2. This response highlights an elevated level of brain activity in response to the pain stimulus. Furthermore, the analysis of oxyhemoglobin and deoxyhemoglobin signals in response to painful stimuli provides a clear sign of hemodynamic changes in the brain. Increased brain activity and energy consumption are correlated with these signals, that pain causes an increase in cerebral blood flow and oxygen consumption is consistent with this observation. Certain frequency bands of the EEG signal, including the alpha, beta, and theta waves, have been associated with the sense of pain. These waves show notable alterations in response to painful stimuli and are recorded at frequencies between 8 and 45 Hz.

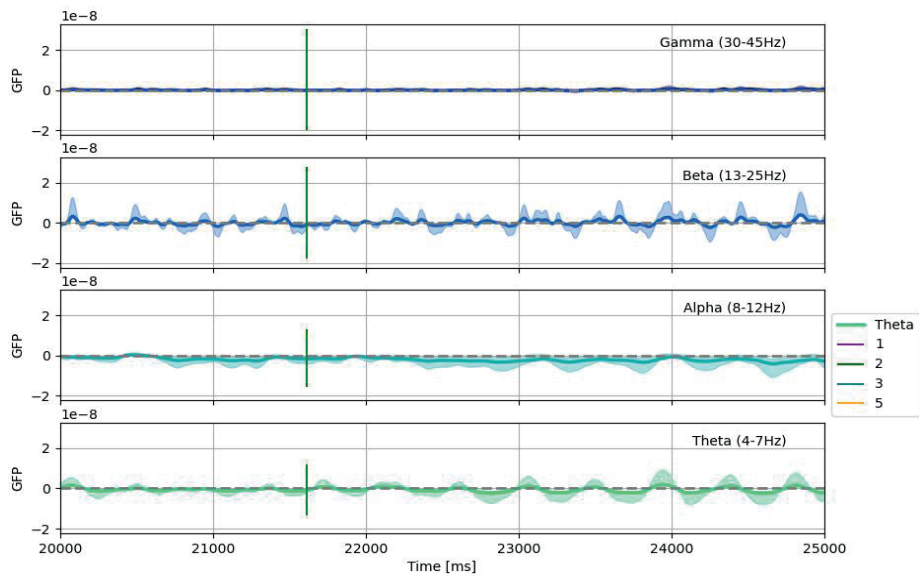

Figure 3. EEG time series

Furthermore, Figure 3 shows that there is a noticeable rise in activity in the theta, alpha, and beta frequency bands after a painful stimulus is applied. The significance of these frequencies in pain detection and interpretation is highlighted by this increased activity,

which emphasizes the brain's reaction to pain.

A strong relationship between brainwave patterns and pain perception is suggested by the elevated activity in particular frequency bands. Increased activity in the alpha band, which is frequently associated with relaxation, may be a sign that pain is interfering with the body's natural resting state. The brain's increased level of alertness in reaction to pain is probably reflected in the beta band, which is linked to active thinking and focus.

A pronounced peak is observed in the beta band around 10,000 ms. This suggests an increase in neuronal activity within that frequency band, which could indicate a state of alertness or cognitive activation at that moment.

The other bands show variations in activity, but not as marked as in the beta band. This suggests that the event or stimulus that triggered this neuronal response had a greater impact on the beta band.

CONCLUSIONS

Understanding brain activity requires the breakdown of EEG signals into frequency bands. Alpha, beta, gamma, theta, and delta bands all are distinct brain functions. Because it records oscillations associated with blood oxygenation and brain activity in response to stimuli, the 1–3 Hz band is essential for fNIRS.

A normal hemodynamic reaction to pain is seen in both EEG and fNIRS signals, with a first rise in oxyhemoglobin and a subsequent decrease in deoxyhemoglobin. Greater brain activity is shown by this reaction, where improved blood flow results from greater oxygen demand. Different brain activity patterns are suggested by subtle variations in the reaction to various painful stimuli.

EEG signals reveal heightened activity in the theta, alpha, and beta bands during pain. The alpha band increases due to the disruption of the resting state, the beta band rises, showing cognitive alertness, and the theta band shows increased activity as the brain processes discomfort.

A pronounced peak in the beta band around 10,000 ms suggests cognitive activation in response to pain. This highlights the beta band's key role in pain perception, with its increased activity offering valuable insights into brain responses to pain.

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