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BIOMEDICAL SIGNAL PROCESSING IN COGNITIVE RESEARCH: BRAIN FINGERPRINTING AND POLYGRAPH TESTING

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This study examines the role of signal processing in Brain Fingerprinting (BF) and Polygraph Testing (PT), two techniques that rely on the acquisition and analysis of biomedical signals. The research examines the methods of biomedical signal processing, including filtering, feature extraction, and classification, to improve accuracy and reliability. Experimental results suggest that advanced electroencephalograph (EEG) signal processing techniques can enhance Brain Fingerprinting applications, while polygraph testing remains widely used due to its accessibility. The findings contribute to the development of more accurate, objective, and non-invasive biomedical signal analysis techniques in cognitive research and neuroengineering.

1. INTRODUCTION

The analysis of biomedical signals plays a fundamental role in understanding human cognition, emotional responses, and physiological states. In recent years, significant progress has been made in signal acquisition and processing techniques, particularly in fields such as neuroengineering, cognitive neuroscience, and behavioral analysis. Among the methods that rely on biomedical signal analysis to assess human responses, two stand out: Polygraph Testing and Brain Fingerprinting.

Polygraph Testing is a classical method that evaluates physiological responses such as heart rate, respiration, and skin conductance, widely used in law enforcement and security settings.

Brain Fingerprinting, on the other hand, is a more recent EEG-based technique designed to detect recognition-related brain responses (such as the P300 wave). It offers a more objective and neurocognitive approach to information detection. Recent studies have proposed EEG-based approaches for biomedical applications [1].

Both techniques require advanced biomedical signal processing, including artifact removal, filtering, feature extraction, and classification. However, their underlying principles differ significantly. BF focuses on neural activity through EEG signal processing, making it more resistant to emotional interference. Meanwhile, PT relies on physiological signals, which can be influenced by stress, anxiety, individual health status or countermeasures.

This study aims to provide a comparative analysis of signal processing techniques used in Brain Fingerprinting and Polygraph Testing, emphasizing their methodological differences, reliability, and applications in biomedical engineering. Unlike previous studies, this work implements a custom EEG protocol using visual stimuli tailored for recognition-based classification, providing new insights into the use of event-related potentials (ERPs) in cognitive signal interpretation. By examining how physiological signals are acquired, processed, and interpreted, this research contributes to the development of more accurate, objective, and non-invasive methods for cognitive and behavioral analysis, drawing on principles from electrical engineering.

2. POLYGRAPH TESTING

Polygraph testing, also known as the “lie detector,” is an investigative method that records and evaluates physiological parameters to assess the truthfulness of a person's statements.

The first polygraph technology was developed in the 1920s when physician and police officer John Augustus Larson combined blood pressure measurement with respiratory monitoring. An improvement to the technique came with the addition of a galvanometer.

The technique gained popularity in the 1940s, being widely used in police investigations and other fields such as national security or employee screening [2]. Over time, the accuracy and validity of polygraph testing have been contested. Nevertheless, polygraph testing continues to be used in various contexts, although it is not considered conclusive evidence in court [3].

The results of a polygraph test reflect changes in the measured physiological parameters [3]. These signals include variations in blood pressure, pulse, respiration, or skin conductivity. It is well known that an elevated heart rate or increased sweating are common indicators of anxiety or discomfort. Therefore, during an interrogation, such physiological reactions may indicate that the person being tested is attempting to conceal the truth. However, it is essential to note that such reactions can also be caused by other factors, not just lying, hence the limitations and controversy surrounding the use of polygraph testing [4].

2.1 PRINCIPLES OF OPERATION

Polygraph Testing operates on the principle that physiological responses are associated with emotional states like anxiety or stress, which are often linked to deception. When a person lies, their body may involuntarily exhibit specific responses, as measured by sensors attached to the subject [5].

These physiological signals, shown in Fig. 1, are continuously monitored and recorded during questioning, with variations analysed to determine whether the subject is attempting to deceive. However, these responses are not specific to lying and can also be triggered by other factors, such as nervousness or fear. Interpreting results can be challenging and sometimes unreliable [6].

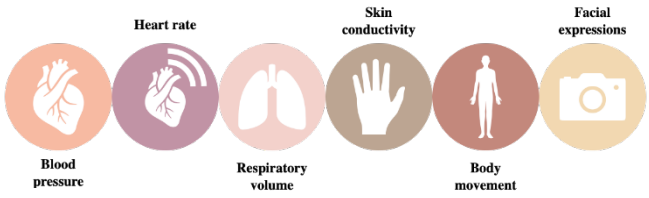

Fig. 1 – Signals of a polygraph test.

2.2 EXPERIMENTAL PROTOCOL

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In a polygraph test, the subject is asked a series of questions divided into two categories: control questions and relevant questions. The goal is to determine if the responses to relevant questions trigger stronger physiological reactions than those to control questions [3]. Typically, the protocol includes the following steps:

– *Subject preparation*: The subject is informed about the procedure and monitored via sensors.
– *Baseline establishment*: Simple questions are asked to establish normal physiological responses.
– *Control questions*: Questions where the subject is expected to lie, unrelated to the investigation.
– *Relevant questions*: Questions directly related to the investigation.
– *Result interpretation*: Physiological responses to relevant questions are compared with those to control questions. Stronger reactions to relevant questions may indicate deception [7].

2.3 SETUP AND EQUIPMENT

Equipment used in Polygraph Testing is designed to monitor and record the subject's physiological reactions in real-time. Several sensors are attached to the tested individual's body to monitor these reactions:

– Blood pressure sensor
– Heart rate sensor
– Respiratory volume sensors (thoracic and abdominal)
– Skin conductivity sensor
– Subject motion sensor (seat-based)
– Video camera pointed at the subject [8].

These sensors provide multiple signals during the test, as shown in Table 1 below.

Table 1
Interpretation of physiological signals [5].

Physiological signals	Normal values	Deception indicators
Blood pressure	120/80 mmHg	Significant increase
Heart Rate	60 – 100 bpm	Sudden increase > 100 bpm
Respiration	12-20 breaths/min	Irregular or accelerated
Skin conductivity	10-50 µS	Increased due to sweating
Body movement	Minimal	Excessive motion, tremors
Facial expressions	Neutral/relaxed	Grimacing, clenching

The monitoring system integrates all these signals to offer a comprehensive view of the subject's physiological reactions during the test. Although these devices are highly sensitive and capable of detecting subtle changes, the validity of the results depends on the examiner's correct interpretation of the data. Each physiological change can have multiple causes, from emotions and stress to deception or dissimulation, which introduces a margin of error into the test.

3. BRAIN FINGERPRINTING

Brain Fingerprinting is a scientifically advanced technique developed to assess whether an individual possesses specific knowledge related to a crime or event by measuring the brain's electrical activity [9].

Created in the 1990s by Lawrence Farwell, this method uses electroencephalography (EEG) to detect the P300 event-related potential (ERP), a brainwave that appears when a subject recognizes familiar stimuli [10]. Unlike Polygraph Testing, which relies on physiological indicators such as heart rate or skin conductance, BF directly targets cognitive recognition processes, offering a more objective means of detecting concealed knowledge.

Despite its precision, BF remains less widely implemented than Polygraph Testing due to its technical complexity and the need for careful selection of stimuli. The technique has found applications in criminal investigations, counterterrorism, and legal settings, where its ability to measure involuntary brain responses offers a reliable tool for identifying whether a person has relevant knowledge that they cannot consciously suppress or manipulate [11].

3.1 PRINCIPLES OF OPERATION

The fundamental principle of BF is that the brain automatically encodes and stores information. When a subject is presented with stimuli related to an event they recognize (such as images, sounds, or words), the brain generates a measurable response known as the *P300 ERP,* as shown in Fig. 2. Unlike Polygraph Testing, which relies on physiological markers linked to emotional responses, BF directly captures neural activity that indicates stimulus recognition.

Fig. 2 – Signals of a BF.

3.2 EXPERIMENTAL PROTOCOL

The experimental protocol of BF involves presenting a set of stimuli to the subject while brain activity is monitored using EEG [10,12,13].

– *Subject preparation*: The subject is connected to an EEG system that monitors brain activity during the test. Electrodes are placed on the subject's scalp to measure electrical signals.
– *Stimulus presentation*: Three categories of stimuli are used:
  o Irrelevant stimuli: Information unrelated to the investigation, used to establish baseline brain activity.
  o Neutral stimuli: Context-related information that the subject is known not to be familiar with.
  o Relevant stimuli: Information directly related to the investigated event (e.g., the weapon used in an attack or the location of a crime), which only the involved person would recognize.
– *P300 response measurement:* Brain activity is recorded and analyzed to detect the P300 response, which occurs when the brain recognizes a relevant stimulus.
– *Interpretation of results:* If the P300 response is detected when relevant stimuli are presented, it indicates that the subject knows those stimuli, suggesting their involvement in the event [11].

3.3 SETUP AND EQUIPMENT

The equipment required for BF primarily includes an EEG system to monitor brain activity and specialized software for data analysis [12].

– *EEG system*: Electrodes are strategically placed on the scalp to capture the brain's electrical activity. These electrodes continuously record brain signals throughout the test.
– *Visual and auditory stimuli*: The test requires presenting either visual stimuli (images displayed on a screen) or auditory stimuli (relevant sounds or words). These stimuli are selected based on the investigation and designed to provoke a P300 response.

EEG data analysis software: After brain activity is recorded, specialized software interprets the data to identify the presence of the P300 response. The results are compared with responses to neutral and irrelevant stimuli to detect possible dissimulation, as shown in Table 2.

Table 2

Interpretation of brain signals [11].

Physiological signals	Normal values	Deception indicators
P300 response	No significant activity to relevant stimuli	Presence of P300 wave after relevant stimuli
Baseline EEG	Normal brain activity	Significant change upon stimulus recognition
Prefrontal Activity	Typical fluctuations	Increased activity during recognition

The EEG system used in BF records precise data, and the P300 response is a clear indicator of the recognition of a specific stimulus. This technique is considered more objective than Polygraph Testing, as it does not rely on physiological reactions that can be influenced by emotions but on direct neurological responses from the brain [13,14].

3.4 THEORETICAL BACKGROUND

3.4.1 EVOKED POTENTIALS (EP)

Evoked potentials (EP) are tiny voltages generated in brain structures in response to specific events or stimuli. These are EEG changes that are elicited and recorded in real-time as a response to sensory, motor, or cognitive events serving as stimuli.

It is believed that they reflect the summated activity of postsynaptic potentials produced when many similarly oriented cortical pyramidal neurons (on the order of thousands or millions) synchronize while processing information [15].

3.4.2 P300 AND P300-MERMER COMPONENTS

The P300 wave is a component of the evoked potential, representing the brain's response to a rare and significant event within a given context. This wave manifests as a peak in amplitude recorded approximately 250-500 ms after the presentation of the unexpected stimulus. Previous studies have demonstrated that the P300 wave can be recorded and identified using various methods, including electroencephalography (EEG) and electrocorticography (ECoG) [9].

3.4.3 BRAIN FINGERPRINTING TECHNIQUE

Brain Fingerprinting is a controversial investigative technique that measures the brain's electrical responses to familiar stimuli, such as words, phrases, or images, presented on a computer screen to highlight recognition. This technique was discovered and developed by researcher Lawrence Farwell in the 1980s as an alternative to the polygraph for assessing the truthfulness of suspects in criminal investigations [16].

Brain Fingerprinting has since evolved into a forensic analysis system that utilizes the measurement of "P300-MERMER" evoked potentials to determine whether an individual recognizes information related to a specific real-life incident. MERMER stands for "Memory and Encoding Related Multifaceted Electroencephalographic Response" and refers to a late negative potential (LNP) extending 1200–1500 ms after the presentation of the stimulus [17].

The technique involves presenting information (words, phrases, or images) on a computer screen that contains prominent details about a crime or situation being investigated, alternating with irrelevant stimuli. When the brain processes information in specific ways, characteristic brainwave patterns can be detected through computerized analysis of brain responses. When an individual recognizes something as significant within the current context, they experience a recognition and recall response related to the event [18].

4. METHODOLOGY AND TOOLS

4.1 EXPERIMENTAL EQUIPMENT

The EEG signal acquisition was performed using a high-performance wearable EEG cap, specifically the g.tec Unicorn. The Unicorn EEG cap provides a non-invasive and precise solution for recording brain signals, featuring a sampling frequency of 250 Hz and a 24-bit resolution. The cap features 8 recording channels, positioned on the scalp according to the international 10-20 system (SI 10-20). The channels used in this study were FZ, C3, CZ, C4, PZ, PO7, OZ, and PO8, carefully selected to cover the key brain areas associated with the P300 wave, as shown in Fig. 3. This setup provides comprehensive coverage of brain regions known to be critical for detecting cognitive responses to stimuli, especially in the context of Brain Fingerprinting and P300 event-related potentials (ERPs) [19].

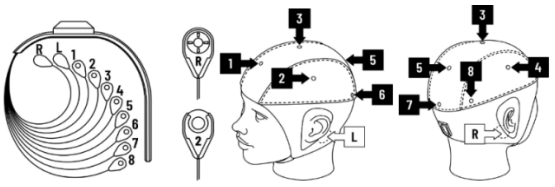

Fig. 3 – Electrode placement on the scalp [19].

4.2 SUBJECT INFORMATION AND CONSENT

Before the experiment began, each subject was informed that the technique used is completely non-invasive and poses no health risks; the test procedure was described in detail. Additionally, the subjects voluntarily provided their informed consent to participate, fully aware of the nature and purpose of the research.

4.3 SIGNAL PROCESSING

Data processing is performed using the MATLAB® numerical computing environment. The evoked potential (EP) signal is obtained by performing synchronized

averaging of the EEG signal. Synchronized averaging is done by temporally aligning the epochs and calculating the arithmetic mean of the EEG signals for each time point. The formula used for averaging is presented in Equation (1) below.

$$S_{med}(t) = \frac{1}{N}\sum_{i=1}^{N} S_i(t), \quad (1)$$

where $S_{med}(t)$ is the averaged signal at time t, N is the number of epochs, and $S_i(t)$ is the EEG signal of the i-th epoch at time t. It is important that the set of signals $S_i(t)$ is acquired under similar conditions: the same acquisition system settings (sampling rate, amplification, filtering) and the same type of stimulation.

5. RESULTS

5.1 PREPARATION OF VISUAL STIMULATION TESTS

This study explores the feasibility of an EEG analysis method for detecting P300 components in Brain Fingerprinting, focusing on methodological validation and signal acquisition optimization. The objectives include ensuring robust EEG acquisition while minimizing participant stress, analyzing waveform parameters beyond amplitude inspection, and assessing the method's applicability in cognitive neuroscience rather than conducting extensive statistical validation.

The experimental protocol for Brain Fingerprinting focuses on recognizing the nature of each presented visual stimulus and evaluating the P300 response, which indicates whether the stimulus is familiar to the subject. The process involves repeated presentation of a stimulus and recording the EEG activity. The recorded EEG signal will consist of many epochs. The evoked potential, where the P300 component is identified, is obtained by averaging the responses for each stimulus to achieve a clear brainwave form. The number of averaged epochs recommended by the literature is 100 for each stimulus to obtain a relevant, clear evoked potential with reduced EEG artifacts [20].

The experiment followed a controlled protocol, and EEG data were processed using advanced filtering and analysis techniques to extract relevant P300 components.

As a result, the set of stimuli was limited to four images: three of unknown individuals and one of a known individual. The order of stimulus presentation varies to prevent anticipation, and each stimulus is displayed for 500 ms, with a 100 ms black screen interval between stimuli. The experiment totals 400 visual and cognitive stimuli, ensuring consistency and reliability of results. A graphical representation of the experimental protocol can be observed in Fig. 4.

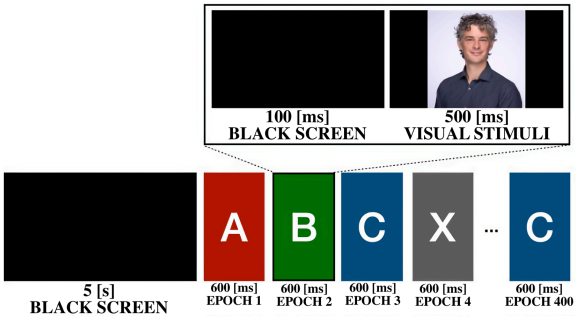

Fig. 4 – Graphical representation of the entire experimental protocol.

5.2 EEG SIGNAL PROCESSING TECHNIQUES

The processing stage of the acquired EEG signal begins with the application of a low-pass filter with an upper limit of 6 Hz, as shown in Fig. 5. This operation is necessary to eliminate unwanted components and emphasize the relevant signals associated with the P300 wave. Filtering is crucial for obtaining clear and well-defined signals, which are essential for the correct analysis of brain responses. Next, the epochs are separated based on the type of the applied stimulus. Each epoch is assigned to a specific class (A, B, C, or X), with class X being of primary interest because it contains specific images considered to have cognitive impact. Once the signals are classified, the EEG signals are averaged to obtain the evoked potential.

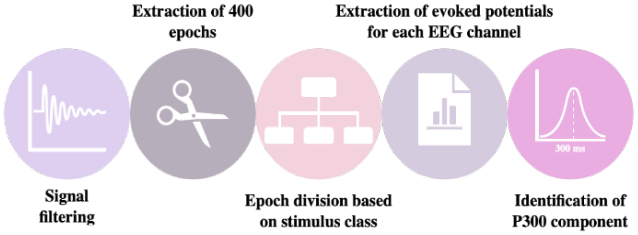

Fig. 5 - Schematic methodology of EEG processing

The signal averaging process was maintained, with special attention to the time window from -100 to 500 ms to fully capture the phenomenon of evoked potentials associated with visual stimuli. Each epoch was rigorously synchronized with the others, ensuring the correct averaging of EEG signals and eliminating any possibility of temporal deviation between the recorded signals.

5.3 PRESENTATION AND INTERPRETATION OF RESULTS

Once the signals undergo processing and the signal evoked through visual and cognitive stimulation is extracted, it can be inferred that results have been obtained. Figure 6 below shows all the evoked potential (EP) signals obtained in the research, for each EEG channel analyzed. The black-colored signals correspond to stimulation with the known image. The remaining signals, colored red, green, and blue, correspond to stimuli from classes A, B, and C, respectively. According to the results, around the 300 ms mark, the presence of a characteristic wave in the EP signals is observed, with a greater amplitude than the rest of the signal, thereby identifying the P300 component in each of these.

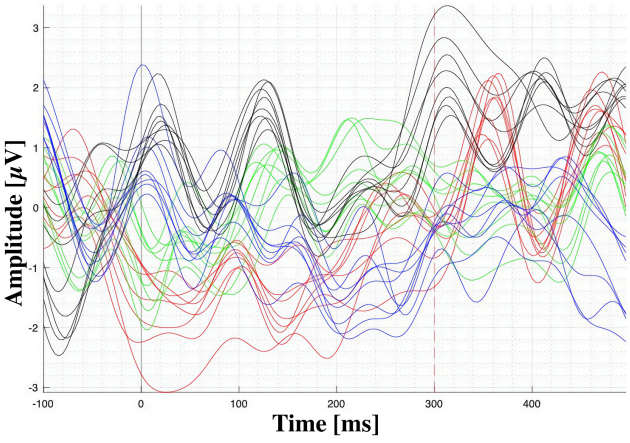

Fig. 6 – Graphical representation of all extracted evoked potentials.

Moreover, it is observed that the maximum amplitudes of the responses to stimulus X reach 3 µV, while the other EP signals (reactions to stimuli of classes A, B, or C) reach maximum amplitudes of about 2 µV.

For a more detailed analysis of the brain response triggered by each type of stimulus, a comparison will be made between the four classes of stimuli used. Each graph represents the evoked potential recorded by each of the 8 acquisition channels within the experimental protocol.

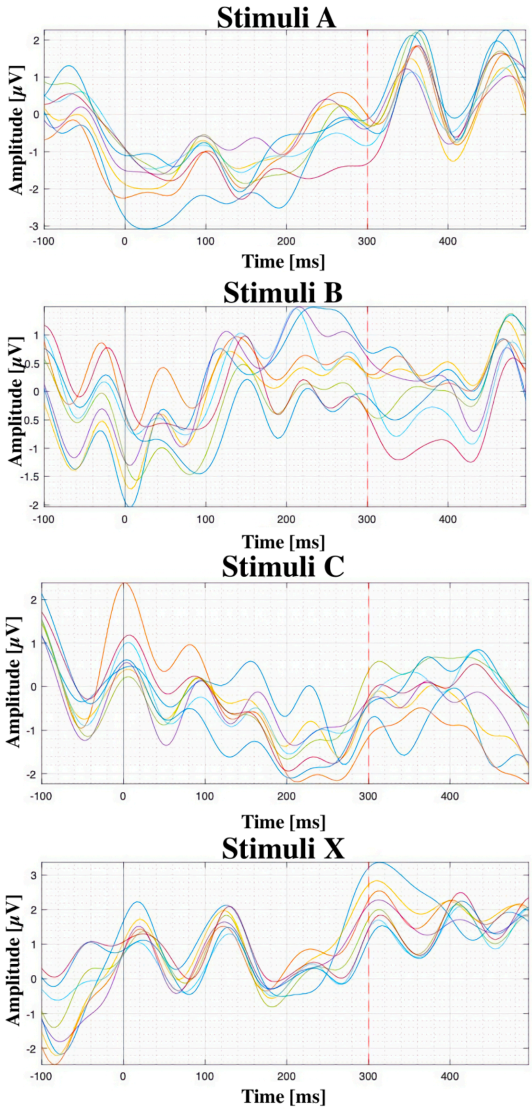

Fig. 7 – Graphical representation of evoked potentials for each type of applied stimulus.

According to the graphical representations of Fig. 7, it is evident that there is a pulsed increase in amplitude around 300 ms, in the case of class **Stimuli X**; the maximum displayed value is 3 µV, compared to the other three representations where no typical P300 components could be identified, and maximum amplitude values are generaly below 2 µV.

Finally, Fig. 8 shows the evoked potentials for each channel. The color code specified earlier for each stimulus is maintained, making it easy to identify the evoked potential of interest, corresponding to stimulus X.

Table 3 presents the amplitude values of the evoked potentials (EP) for each type of applied stimulus (A, B, C, X) and each EEG channel (Fz, P3, Cz, P4, Pz, PO7, Oz) at the time instant of 300 ms.

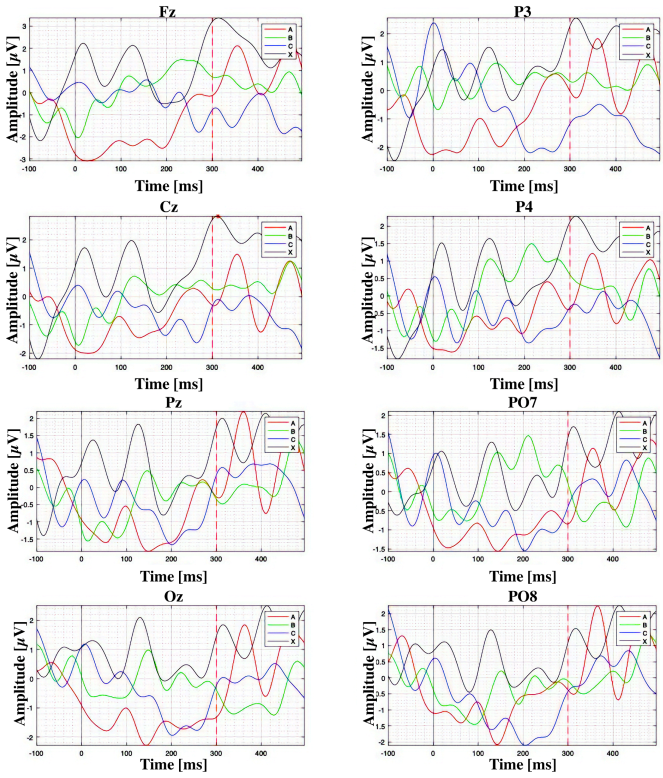

Fig. 8 – Results obtained for each analyzed EEG channel.

Table 3

Amplitude values of the P300 wave.

	Stimulus A [µV]	Stimulus B [µV]	Stimulus C [µV]	Stimulus X [µV]
Fz	-0.173	0.712	-0.823	**3.205**
P3	-0.017	0.326	-1.192	**2.237**
Cz	-0.312	0.287	-0.313	**2.684**
P4	-0.398	0.602	-0.322	**2.198**
Pz	-0.285	-0.357	0.412	**1.723**
PO7	-0.852	0.214	-0.397	**1.407**
Oz	-1.432	-0.428	-0.195	**1.532**
PO8	-0.401	-0.110	-0.402	**1.121**

It can be observed that stimulus X generates the highest amplitude values for the evoked potential (EP) compared to the other stimuli, thus confirming its significant influence on the measured brain activity.

6. LIMITATIONS AND FUTURE WORK

This research focused on a limited sample size and a controlled visual stimulus protocol, which may affect the generalizability of the results. Future work should include:

– Increasing the number of participants for more statistically significant results.

– Introducing rest intervals during testing to reduce participant fatigue and improve signal clarity.

– Diversifying visual and auditory stimuli to assess broader cognitive reactions.

– Implementing machine learning classifiers for automated detection of P300 components.

– Collaborating with experts in cognitive neuroscience and legal psychology to validate Brain Fingerprinting in real-world scenarios.

7. CONCLUSIONS

The comparative analysis of Polygraph Testing and Brain Fingerprinting highlights the significant technological and

methodological differences between the two techniques used to assess emotional versus mental reactions to cognitive stimuli. Both methods have their strengths and limitations, and their applicability depends mainly on the specific context in which they are used.

The experimental results presented in this research demonstrate the ability of Brain Fingerprinting to distinguish between different classes of visual stimuli, identifying cognitive aspects embedded in the images used as stimuli. Specifically, the P300 wave has proven to be a robust marker for recognizing known stimuli (target) compared to unknown ones (no_target).

The analysis of P300 wave amplitudes highlighted significant differences between the stimulus classes, with maximum amplitude values recorded for stimulus X (target) compared to stimuli A, B, and C (no_target). This observation suggests more potent and more specific neuronal activation in response to known stimuli, validating the hypothesis that the P300 wave is an indicator of cognitive processes involved in recognizing and processing relevant information.

To improve and expand the research, it is proposed to increase the sample size for more representative results, optimize the experimental protocol by reducing the duration and introducing breaks, diversify the visual stimuli for a deeper understanding of cognitive processes, use advanced EEG signal processing techniques such as machine learning algorithms, and explore clinical and forensic applications by collaborating with cognitive neuroscience experts to validate and implement Brain Fingerprinting in various fields.

In future developments, the integration of artificial intelligence methods, such as machine learning algorithms, could significantly improve the detection and classification of P300 responses.

These techniques may enable real-time analysis, noise resilience, and automated interpretation of EEG signals, thereby expanding the applicability of Brain Fingerprinting in both clinical and forensic settings.

BIOETHICAL CONSIDERATIONS

This study was conducted under international ethical guidelines for biomedical research. Participants were informed about the procedure, and informed consent was obtained. The experimental protocol was designed to minimize discomfort and ensure optimal conditions. The study aims to validate an EEG-based method (P300) by establishing technical application conditions. The focus is on methodological evaluation rather than extensive quantitative analysis.

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