Validation Methodology of Wireless Brain-Computer Interface for Event-Related Potential Application

Ádám Salamon, Gábor Takács, and György Bognár

***Abstract*—Electroencephalography (EEG) is a technique used to observe brain activity by measuring the dynamic changes of the electric field induced by neurons' activity. Brain-computer interface (BCI) systems are used in cognitive psychology examinations measuring the changes of brain activities. This paper presents a validation methodology to characterize BCI systems with wireless communication interface and the applicability on a preselected BCI system. This way, the delay, the functionality, and the frequency selectivity can be determined of the overall BCI system, taking into account the effect of the hardware, the software, and the electrodes, avoiding noise artifacts. The presented and validated BCI system proved to be successfully applied in ERP EEG measurements such as steady-state visually evoked potential, pattern-reversal visually evoked potential, and P300 event-related potential.**

***Index Terms*—Biomedical communication, Biomedical electrodes, Biomedical electronics, Biomedical engineering, Biomedical measurement, Biomedical signal processing, Brain modeling, Brain-computer interfaces, Electroencephalography.**

I. INTRODUCTION

Electroencephalography (EEG) is a commonly used technique to observe brain activity by measuring the dynamic changes of the electric field induced by the neurons. EEG provides excellent time domain and weaker spatial resolution of the brain activities and can show the functional state of the brain and its dynamic changes. Special brain-computer interface (BCI) systems are applied to different cognitive psychology examinations to measure the changing electrical activity of the brain. The validation of these BCI systems has to be carried out to determine the signal-to-noise ratio, the delay time, and exact applicability.

Although various heterogeneous validation techniques exist, only the American Clinical Neurophysiology Society (ACNS) provides standardized guidelines for the clinical use of EEG systems [1]. The methodology approaches presented in this paper are based on this guideline. However, the worked-out characterization methodology for BCI systems focuses on the most frequently applied event-related potential (ERP) measurements in cognitive psychology examinations (e.g., instead of P100, P300 was measured). The ERP is a non-invasive neuroimaging technique measuring the brain's electrical activity in response to a specific event or stimulus.

This paper presents the validation methodology for BCI systems with wireless communication interface toward a personal computer.

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By the proposed methodology, not only the hardware part of the signal processing can be measured and validated, but also the effects of the software component(s), the electrodes, and the overall system. (Figure 1.)

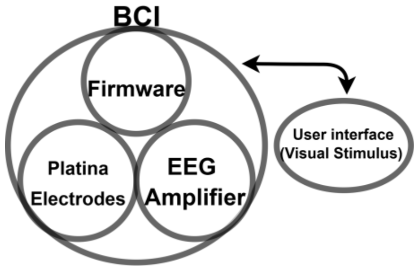

Figure 1.: BCI headset components and visual stimulus.
[2, Fig. 1 adapted]

In this paper, the application of the developed characterization methodology on a selected BCI system (Figure 2.) intended for event-related potential (ERP) examinations is presented in detail.

Initially, a single photodiode was applied to simulate a simplified brain model. This approach allowed for precise characterization of the system's latency without measuring the additional noise introduced by the human brain and body. This setup made it possible to isolate and identify any intrinsic system-level deviations or artifacts that might affect signal integrity.

In the following steps, event-related potential measurements on multiple human subjects were carried out. This step aimed to assess the practical applicability and performance of the BCI system under real-world conditions, specifically evaluating whether the system fulfills the event-related potential (ERP) application requirements (can be seen in Table I.). These requirements typically include aspects such as signal clarity, timing accuracy, and the system's ability to detect event-related/evoked neural responses consistently across different individuals.

The presented methodology, combining both hardware-based testing and subject-based ERP experiments, demonstrated its applicability for validating BCI systems intended for ERP applications.

This approach ensures that technical performance and biological compatibility are thoroughly investigated. It also offers a robust framework for selecting and validating BCI platforms in non-invasive neuroimaging research and development.

Section II provides a concise overview of EEG fundamentals and different ERP measurement techniques applied in cognitive psychology examinations, which are summarized to give a solid background in this specific field of neuroscience.

Section III describes the validation methodology and the developed characterization system.
Section IV presents the selected BCI system in detail.
Section V discusses the characterization and measurement results.

Figure 2.: BCI headset prototype (flexible headset, measured area, electrodes).

II. THEORETICAL BACKGROUND

A. *Electroencephalography*

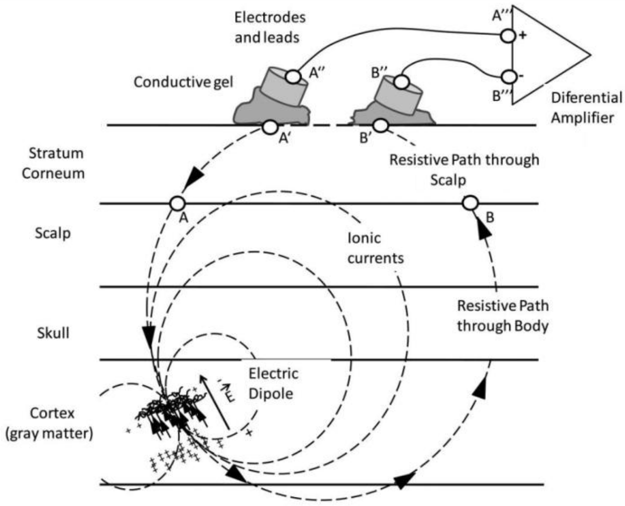

Figure 3.: Electric dipoles created by the postsynaptic potentials and EEG measurement. [3]

The extracranial EEG signals are observed on the surface of the hairy scalp, but several attenuating factors influence the signal (Figure 3.). Therefore, a synchronous potential change of at least 6-10 cm^2 of the cerebral cortex is required to achieve an evaluable signal-to-noise ratio [1], [2]. The attenuating factors significantly narrow the range of brain activities that can be examined and studied. With this limitation, EEG is still effectively used in neurological research and BCI applications [4], [5].

B. *Neurons' activities*

Neurons show two electrical activities: action potential and postsynaptic potential change. The action potential is triggered when the internal potential of the neuron reaches a value above a threshold level as a result of a stimulus from dendrites [6]. At this point, a self-sustaining (70–110 mV) potential change of the order of a millisecond extends from the cell to the ends of the axon [7], [8]. The time course and amplitude of the potential change are constant for the given cell. If the stimulus reaches the activation threshold, it is no longer independent of its parameters. In most cases, an action potential cannot be detected with electrodes placed on the scalp, except only in auditory-induced cerebral responses satisfying conditions for sensing the action potential change where several axons run in parallel.

In the EEG studies presented in this paper, the electric signals received with the electrodes are caused by postsynaptic potential changes in cortical pyramidal cells. Unlike the action potential, postsynaptic potential changes are graded potentials (100 µV to 10 mV) with slower (5 ms to 30 ms) duration [7]. The neuron performs the summation of the excitatory and inhibitory postsynaptic potentials. Excitatory postsynaptic potential brings the neuron closer to the action potential threshold, and inhibitory postsynaptic potentials move the neuron away from the action potential threshold [9].

Cortical pyramidal cells neurons are oriented parallel to each other, and the field electrical dipole generated by the postsynaptic potential can be measured with EEG through the scalp. (Figure 4.)

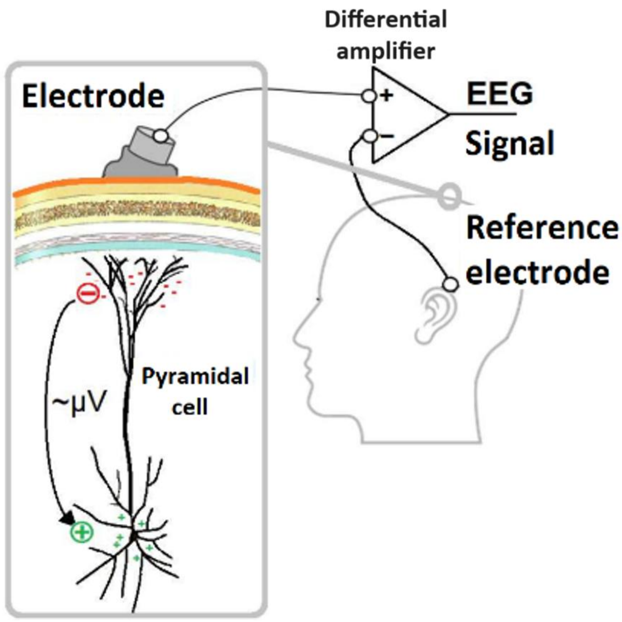

Figure 4.: Postsynaptic potential change in the pyramidal cell creates an electric dipole in the area around the neuron.

C. *International 10-20 System for electrode placement*

The 10-20 electrode placement system is the first and still accepted standard for defining and naming electrode positions. In this system, 21 electrodes are placed at 10% and 20% relative distances along the skull. (Figure 5.) Later, more electrode positions were added to the standard called 10-10 systems. Further extensions, like 5-10 systems and other electrode systems (that increased the number of electrodes) are used by vendors but still not accepted as clinical EEG nomenclature standards [10].

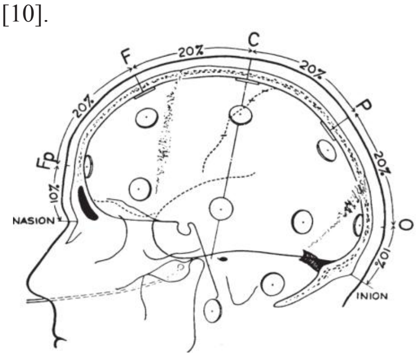

Figure 5.: International 10-20 System. [11].

D. Event-Related Potential

Event-related potential (ERP) is a direct response to a specific sensory, cognitive, or motor event of the brain [12]. BCI interfaces usually use these potential changes to determine user intentions.

The EEG signal represents many ongoing brain processes; therefore, a single event is invisible. Many trials are recorded and averaged to extract the specific brain response.

The signal-averaging procedure is used to extract event-Related Potentials from the EEG signal. This technique applies the following assumptions:

1. ERPs are invariable to signal latency and morphology.
2. The noise can be approximated by a zero-mean Gaussian random process uncorrelated between trials and not time-locked to the event.

Noise cannot be related to brain functions, muscle movements, and external electric fields. Averaging improves the signal-noise ratio with $\sqrt{N}$, where N is the number of epochs:

$$x(t) = ERP(t) + noise(k,t)$$

$$\bar{x}(t) = \frac{1}{N}\sum_{k=1}^{N} x(t,k) = ERP(t) + \frac{1}{N}\sum_{k=1}^{N} noise(t,k)$$

x represents an epoch of the recorded EEG during a trial, k is the epoch number, and *t* represents the time elapsed after the event.

The naming convention of event-related potentials follows the following rule:

- The first letter shows the potential change direction:
  - P – positive,
  - N – negative,
  - C – not defined.
- The following number defined the ordinal position of the peak in the waveform or the latency of the peak (e.g., P300 for a peak at 300 ms).

ERP component names can often be confused. Multiple ERPs can have the same name, but it can mostly be easily determined from the context [13].

E. P300 Event-Related Potential

P300 is a commonly used event-related potential (ERP) in BCI applications. Two P300 components are distinguished (P3a, P3b), most cases P300 means P3b component. (Figure 6.) The P300 is a positive amplitude EEG wave that occurs during decision-making and information processing. P300 has a peak latency in the range of 250–750 ms. P3b usually appears as a result of a very surprising stimulus, the amplitude of which correlates with the probability, complexity, and form of the appearing stimulus. P300 depends on the energy invested in the task and its complexity. The amplitude of the response increases with the complexity and power of surprise of the task as well.

P3a is sensitive to the context of the stimulus, and its amplitude decreases as the subject becomes accustomed to the stimulus. That is why P3a is not ideal for most BCI applications.

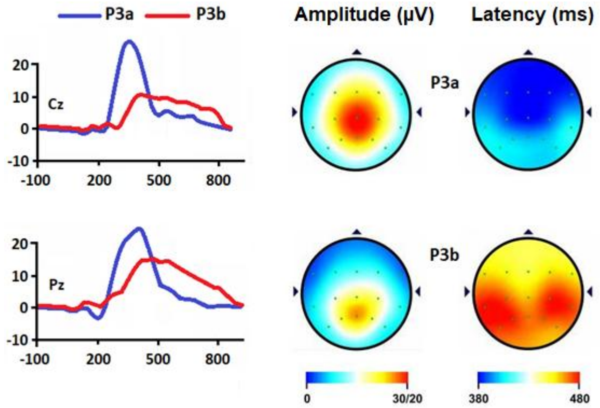

Figure 6.: P3a component is frontocentral and has a peak in the range of 250-280 ms. P3b component is parietal and has peaks around 250-500 ms after the trigger stimulus [14]

The oddball paradigm is used in a typical ERP experiment for evoking P300. (Figure 7.) Where ~80% of the stimuli are standards, and ~20% are deviant. These stimuli can be visual or auditory. Typical tasks are to count the number of deviants. If the presented stimulus is deviant, the subject of the study has to make the decision, and after that, a particular, well-defined task should be made. This decision evokes P300. In BCI applications, multiple stimuli are presented, and investigating the corresponding P300 response in the EEG signal can indicate the person's intentions. P300 spellers usually use this method.

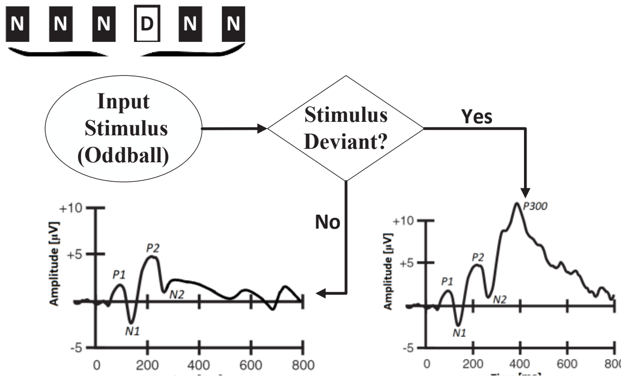

Figure 7.: Oddball paradigm, the subject makes a decision which evokes the P300.

F. Steady-State Visually Evoked Potential

Steady-state visually evoked potential (SSVEP) is a natural response of the visual cortex to a periodic visual stimulus of the retina. The elicited SSVEP response has the same frequency in the EEG signal as the stimulus. SSVEP is strongest at the occipital region (at O1, O2 electrode positions, see Figure 9.). Visual stimulus frequency can be between 3,5–75 Hz.

SSVEP has a high communication rate due to its excellent signal-to-noise ratio, easy configuration, and user training. The limitations of SSVEP in BCI applications are the monitor's (on which the periodic visual stimulus appears) frequency and area. Visual stimulus frequency should be an integer divisor of the monitor frequency.

BCI users are instructed to focus on the corresponding stimulus: a light source or a bright area on a monitor. (Figure 8.) To this stimulus, the visual cortex response (the SSVEP) can be observed in the corresponding electrodes EEG signal.

Only a limited number, around four to six, of stimuli can be efficiently presented to the user. Increasing the number of stimuli creates an overlap in the user's field of vision; thus, the SSVEP generated by the effect of more stimuli appears in the EEG, which reduces the signal-to-noise ratio.

SSVEP has a robust frequency characteristic: the frequency coding method, which assembles different flickering frequencies into multiple targets, has been widely used in BCI applications [15].

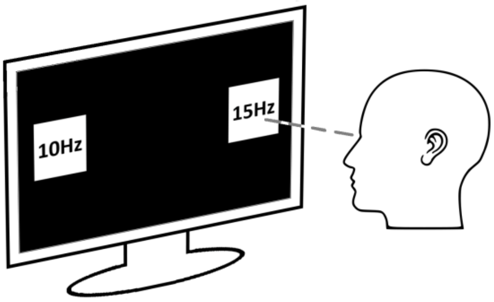

Figure 8.: SSVEP measurement setup, visual stimuli appear on the monitor screen.

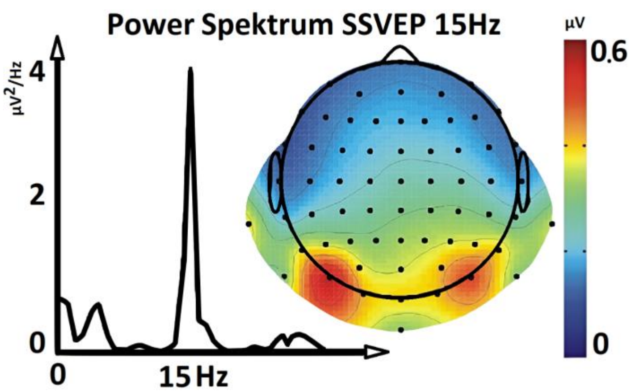

Figure 9.: SSVEP measurement and distribution. [16], [17]

G. Pattern-Reversal VEP

In the clinical use case, visual evoked potentials (VEPs) test the functional integrity of the anterior visual pathways, measured above the visual cortex. For the majority of clinical applications, the pattern-reversal VEP is considered the preferred and most reliable method due to its consistency in timing and waveform, which is less prone to variation compared to other VEP techniques [18]. Therefore, it is ideal for testing purposes.

To evoke Pattern-Reversal VEP event-related potential, the visual cortex is stimulated with a checkerboard visual stimulus (Figure 10.). This visual stimulus alternates a checkerboard image and its inverse in the visual field with a given frequency of 0.5–1.5 Hz. This pattern keeps a constant luminous intensity.

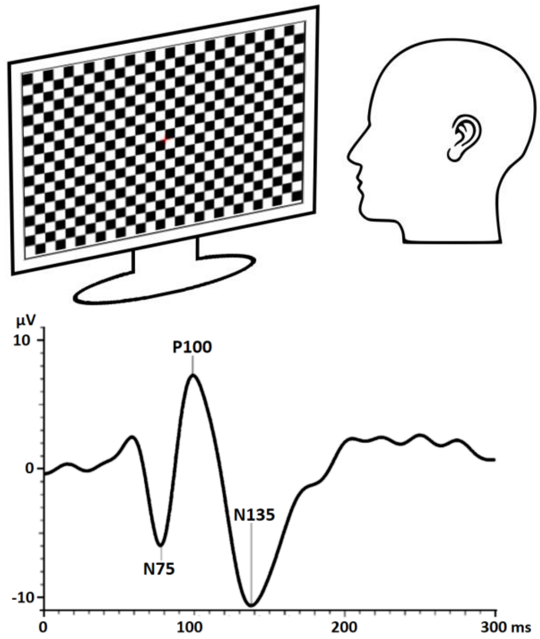

Figure 10.: Chequerboard stimulus and the evoked Pattern-Reversal VEP. [18]

III. RESEARCH MOTIVATION

The primary aim of this research is to develop and validate a robust methodology that can effectively characterize and evaluate different BCI systems, specifically those employing wireless communication interfaces. This validation framework focuses on crucial performance metrics, such as system delay, functional accuracy, and frequency selectivity. Importantly, it also addresses the common challenge of noise artifacts, which can distort EEG measurements and compromise system reliability.

Through systematic validation, this study seeks to demonstrate the applicability of the proposed methodology on a selected BCI system. The validated system will be applied in capturing event-related potentials (ERPs), including steady-state visually evoked potentials (SSVEP), pattern-reversal visually evoked potentials, and the P300 event-related potentials, showcasing its practical utility and reliability in cognitive and clinical EEG assessments.

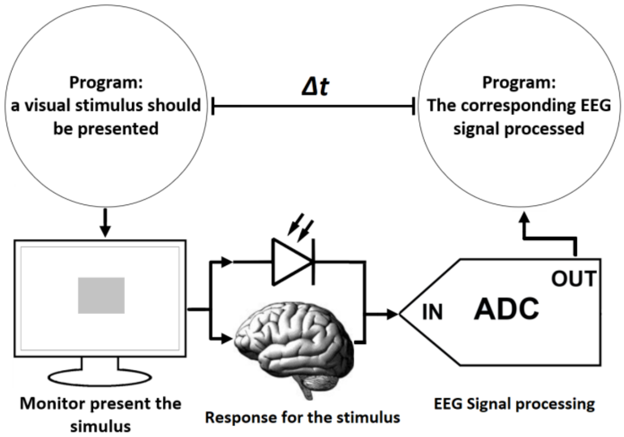

Figure 11.: Validation framework with brain model and in vivo.

IV. Validation Methodology and Framework

The system architecture of the validation framework can be seen in Figure 11. During the validation and characterization steps, a 24-bit analog-to-digital converter (ADC) was applied, which is directly developed for EEG purposes. The AD converter circuitry consists of a preamplifier, and the digital data is transmitted to the measurement control computer through a wireless fidelity (Wi-Fi) connection. C#-based program running on the computer was responsible for handling and displaying the desired image content (shapes, chequerboard, etc.) and setting the timer to zero. A self-developed MathWorks MATLAB tool was developed and applied to process the incoming signals.

First, the validation framework was tested without electrodes, applying triangle and square waves directly to the inputs. The analog-to-digital converter (ADC) measured the signals' correct morphology, amplitude, and frequency. Further testing of the ADC without the electrodes is not needed at this point. This test shows that the ADC is successfully integrated into the system.

A. Test configuration with the brain model

The brain-computer interfaces that use a photodiode (SFH 2701) operated in photoconductive mode as visual stimuli can also be used as brain models (Figure 12.). The whole system (event generation, visualization, signal measurement, and processing) can be tested with this simple brain model.

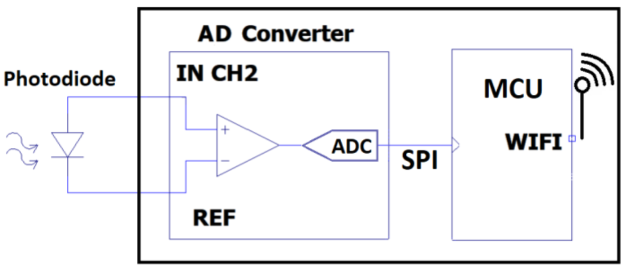

Figure 12.: The test configuration with the brain model.

The brain model creates low-latency and repeatable signals without the noise artifacts created by the brain and the human body. By applying this model, the Δt latency can be measured between the trigger impulse and the measured EEG signal. This method can be used to create a perfect stimulus-ERP synchronization. (Figure 13.)

The brain model measurements show that the tested BCI has a Δt latency with a Gaussian distribution. The latency is random and stays in a 35-55 ms range 94% of the time, as it can be seen in Figure 14. This result is acceptable for most ERP experiments based on the following measurements presented in Section V.

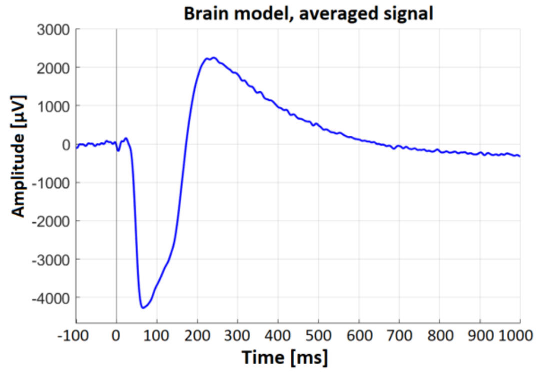

Figure 13.: Brain model measurement to determine the average Δt latency.

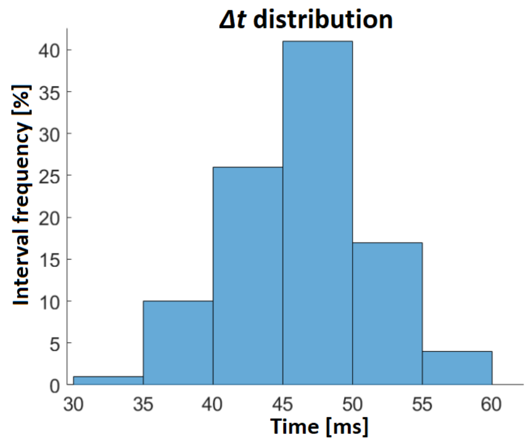

Figure 14.: Brain model measurement Δt latency standard deviation.

However, another acceptance level can be determined based on the morphology of the ERP signal to be measured. More trials lead to significant signal degradation, as it can be seen in Figure 16.

The epochs are defined with trigger impulses. Therefore, the Δt-latency dispersion creates an additional error during the signal averaging (Figure 15 and Figure 16).

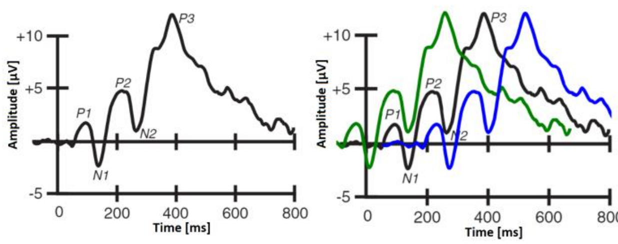

Figure 15.: P300 Δt latency dispersion creates an additional error.

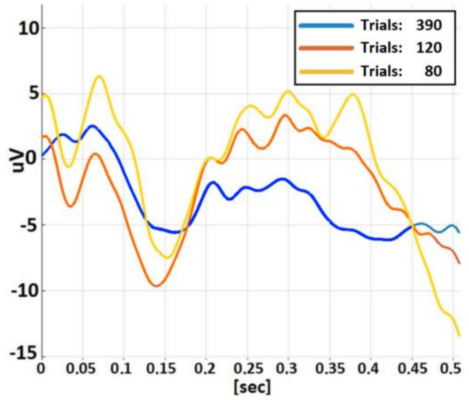

Figure 16.: Signal degradation due to insufficient Δt latency distribution.

B. *Test configuration with a BCI device*

A Mindrove BCI headset applied in our investigations observes brain activity through six configurable semi-dry platinum electrodes, one reference electrode, and one bias electrode [19], [20]. The lack of conductive gel and the use of platinum instead of silver chloride electrodes lead to an acceptable – but decreased – signal-to-noise ratio, higher electrode impedance and DC offset [21], [22], [23]. On the other hand, omitting the conductive gel and using more durable electrodes creates a better user experience.

The headset applies a 24-bit analog-to-digital converter designed explicitly for EEG measurements with a built-in 24x input gain amplifier and 500 Hz sample frequency. The headset uses 2.4 GHz frequency wireless transmission to connect with the PC client program.

TABLE 1.
EXAMPLE TECHNICAL SPECIFICATIONS REQIREMENTS COMPLIANCE FOR BCI SYSTEMS

	MINIMUM TECHNICAL REQUIREMENTS [1]	Tested Device
Electrodes material	Silver—silver chloride or gold disk electrodes recommended, other materials and electrode pastes can be used.	Platina- Iridium electrode
Electrode placement nomenclature:	10 to 20 System recommended, or 10 to 10 System can be used	10 to 20 System
Electrode Impedace:	100 Ω < R < 10 kΩ with balanced impedances	16 kΩ< R <50 kΩ
Sampling rate	256 Hz minimum, 512 Hz preferable	500 Hz
AD converter resolution	16 bit minimum, 24 bit or more is preferable	24 bit
EEG resolution	<0.05 µV	0.022 µV
Common mode rejection ratio	90 dB minimum, and preferably higher	110 dB
Additional amplifier noise in the recording	< 1µV peak to peak at any frequency 0.5 - 100 Hz, including at 60 Hz	1.39 µV peak to peak
Trigger Latency	not specified	35-55 ms

V. VALIDATION OF WIRELESS BCI WITH EVENT-RELATED POTENTIALS

Open/closed eye alpha rhythm (Berger effect) measuring is usually the widely used way – and the first step – to test basic functionality of the validation framework. Alpha wave is in a relatively narrow frequency range. However, amplitude can be varied by the mental process and mental states [3] SSVEP amplitude can also be affected by these, but it is considered acceptable for BCI device validation.

A. *SSVEP*

Steady-state visually evoked potential (SSVEP) is a robust, noise-tolerant ERP, measured over the visual cortex at O1 and O2 electrode positions. SSVEP is a time-independent ERP. The evoked response can be easily distinguished in the EEG amplitude spectrum. The ERP processing algorithm is based on computing the discrete Fourier transform. Therefore, SSVEP is optimal for the BCI test, where periodic noises could occur in the EEG signal. A lower frequency (<20Hz) stimulus creates a higher amplitude response. SSVEP is most sensitive to 15 Hz stimulus frequency. BCI was tested with a flashing LED light and a rectangle on the monitor, and measured at the subject's O1 electrode position. The tested BCI measured SSVEP correctly in both experiments. The EPR signals are present in the EEG recording with adequate amplitude (Figure 17. and Figure 18.).

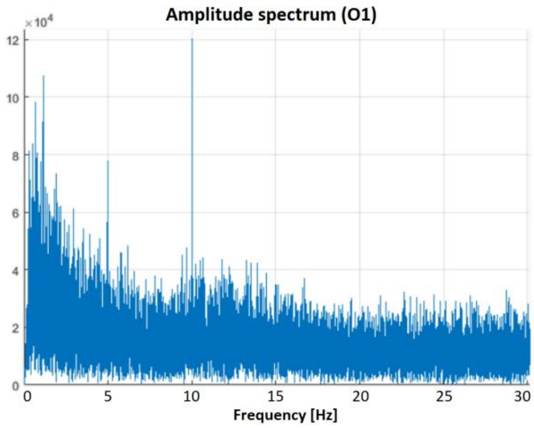

Figure 17.: SSVEP measurement with 15 Hz LED.

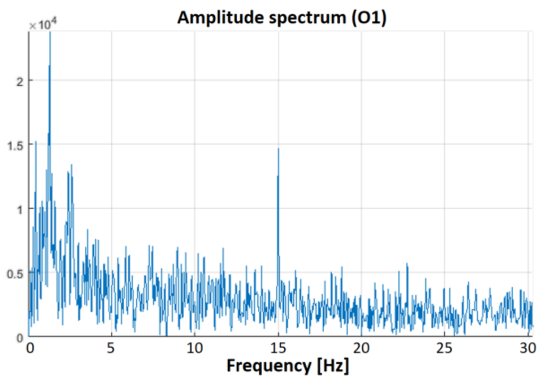

Figure 18.: SSVEP measurement with 10 Hz white rectangle.

B. Pattern-Reversal VEP

Pattern-Reversal VEP experiment focuses on the correct timing. And also the recommended testing ERP for clinical use EEG systems, by the American Clinical Neurophysiology Society [1]. The ERP signal had a definite ~30 ms wide positive amplitude. Pattern-Reversal VEP was also measured at O1, and the electrode placement was the same as SSVEP discussed before. The signal-to-noise ratio can be easily increased by incrementing the number of epochs. 1 Hz stimulus frequency creates plenty of ERP for measurements.

This ERP measurement shows whether the trigger impulse and the observed event timing are synchronized.

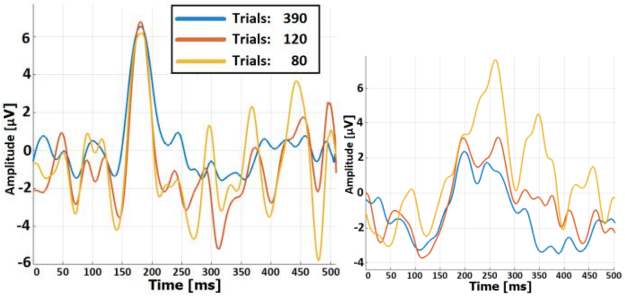

Figure 19.: Pattern-Reversal VEP measurements
Averaging different numbers of trials.
(left: small standard deviation Δt, right: large standard deviation Δt)

In Figure 19., the left figure shows the Pattern-Reversal VEP with correct timing, and the right one shows another Pattern-Reversal VEP measurement, where Δt latency stays in a 50 ms range 50% of the time. The inaccuracy of Δt stretches out the detected ERP signals, and it can be seen in Figure 19. that the maximums of different numbers of trials are at different places on the function.

C. P300 ERP measurements

P300-based spellers are widely used due to the relatively high information throughput. P300 is evoked via a visual oddball paradigm shown in Figure 20. P300 is sensitive to the stimulus, and a familiar face can evoke a more distinct signal modality and better evaluation speed [24].

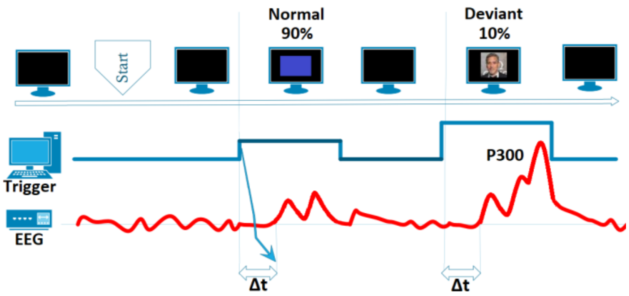

Figure 20.: P300 oddball paradigms stimuli.

The oddball paradigms stimuli were presented with 1 Hz frequency, and stimuli were presented at the monitor for 0.1 sec. The probability of the deviant paradigm was Pd=0.1. (Figure 20.)

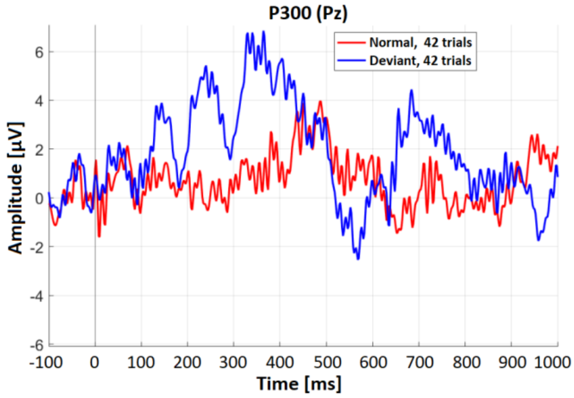

Figure 21.: P300 measurement platina electrode + NaCl.

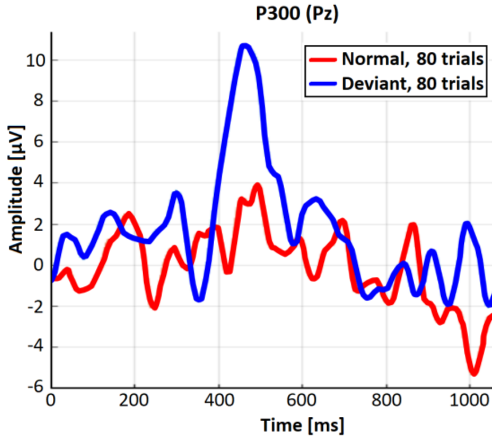

Figure 22.: P300 measurement platina electrode + Abralyt HiCl 10% gel

The measurements were recorded at a sampling rate of 500 Hz and band-pass filtered between 1 and 90 Hz. Power line interference at 50 Hz was eliminated, and additional artifacts were manually removed from the EEG signal. (Figure 21. and Figure 22.)

In Figure 22., it can be seen clearly that the deviant stimuli caused higher, detectable amplitude at around 300 ms, and the amplitude is approximately three times greater than the amplitude of the normal stimuli curve.

VI. CONCLUSION

The primary aim of our work was to develop a methodology strictly focusing on ERP examinations. Thus, it is possible to determine whether the BCI system under investigation can be used in ERP experiments.

- The ACNS Guidelines outline the minimum system requirements for clinical EEG systems. While these standards should be applied to BCI systems, their use is not mandatory.
- Crucial performance metrics such as system delay, functional accuracy, and frequency selectivity should be validated for the whole system with the corresponding ERPs.

- SSVEP for frequency selectivity validation. It is one of the mainly used ERP in BCI systems, and is not affected by system's overall latency.
- Pattern reversal VEP due to low variability in timing, amplitude, waveform morphology, and validation can be performed at relatively high stimulus frequency.
- The presented brain model can be used to determine the system's overall latency (Δt), and its distribution.
- P300 is the most common ERP used by BCI systems, amplitude, waveform morphology can be determined. However, it exhibits greater variability than Pattern reversal VEP.

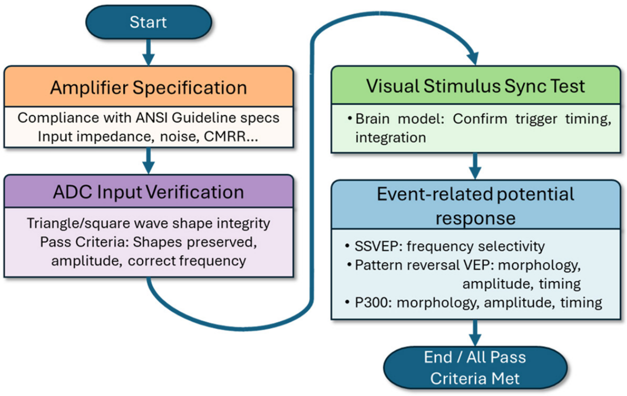

Figure 23.: Measurement and validation steps.

Measurement and validation steps were carried out, and the results proved the applicability of the validation methodology. The developed validation methodology can be seen in Figure 23. It includes not only the mandatory steps but also the key characteristic parameters that must comply with the technical specification requirements for BCI systems. The characterized BCI system was proved to be applied in ERP EEG measurements such as steady-state visually evoked potential, pattern-reversal visually evoked potential, and P300 event-related potential. The developed validation methodology is suitable for testing and validating similar BCI systems.

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