ORIGINAL ARTICLE

A Wearable Device-Based System: The Potential Role in Real-time and Remote EEG Monitoring

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Abstract

Purpose: In recent years, the Electroencephalography (EEG)-based Brain-Computer Interface (BCI) application has been growing rapidly and has emerged as a technology with high translational potential since it allows disabled people to translate human intentions into control signals and to interact with the external environment without any kinesthetic movement. Individuals with significant health problems can benefit from this technology to improve their independence and facilitate participation in activities, thus improving general well-being and preventing impairments. The rapid advances in technology have led to optimal innovation in the context of wearable health monitoring and remote-control solutions. Many wearable devices for capturing EEG signals in daily life have recently been released on the market. Our paper aims to present a wearable de-vice-based system for real-time and remote EEG monitoring, to describe the proposed system modules and the signal processing algorithms, to explore the functionalities of this wearable EEG solution, and to suggest its potential application for daily brain data recordings in the home environment.

Materials and Methods: The validity of the Emotiv Epoc+ device in the continuous and real-time EEG signals acquisition and monitoring was demonstrated by means of preliminary test measurements during a resting state paradigm performed by a healthy control subject.

Results: Our findings confirmed the Epoc+ reliability for event-related brain potential research and in measuring acceptable EEG data.

Conclusion: The described approach, focusing on the emerging area of remote monitoring sensors and wearable device applications, might be leveraged to measure complex health outcomes in non-specialist and remote settings.

Keywords: Wearable Electroencephalography; Consumer-Grade Electroencephalography Devices; Signals Processing; Remote Monitoring.

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1. Introduction

In recent years, the Brain-Computer Interface (BCI) application has been growing rapidly, establishing itself as an emerging technology able to translate human intentions into control signals and allow disabled people to interact with the external environment without any kinesthetic movement [1]. More specifically, electroencephalography-based Brain-Computer Interface (EEG-based BCI) has emerged as a technology with high translational potential owing to its desirable traits: direct measures of neural activity, portability, non-invasiveness, and inexpensiveness [2].

The epidemiological context of the coronavirus disease 2019 (COVID-19) pandemic, imposing severe restrictions on individuals' participation in daily living activities, mobility, and transport, was an unprecedented opportunity to speed up the development of wearable devices, mobile sensing technologies, telemedicine services, and remote-control approaches [1].

The field of electroencephalography has observed dramatic advances in the last decade, focusing on emerging state-of-the-art EEG tools that enable flexible recording of brain activity in real-time. This new trend in the EEG context was initially driven by an interest in incorporating real-time neural pattern recording into consumer-oriented applications, including developing brain-computer interfaces [3-5]. It has been facilitated by the rapid advances in system-on-a-chip technology and the increasing miniaturization of sensors and circuitry. The improvements in this next-generation neuroscientific technology have fueled the need for EEG recording approaches that are inexpensive, non-invasive, portable, increasingly more available, and appealing to everyday users, thus suitable for re-al-time and remote monitoring.

State-of-the-art literature in the context of electroencephalographic systems reported various wearable out-of-hospital solutions that can provide accurate recordings and offer several benefits in daily monitoring [6-8].

Several studies aimed at validating the reliability of proposed systems for Event-Related brain Potential (ERP) research, frequently comparing the continuous EEG measurements using portable devices and research-grade ones [9-16].

Few other studies tried to provide a highly portable solution suitable to remotely collect frequent data from patients in home settings and to continuously mobile EEG data monitoring, demonstrating the translation and application of neuroscientific knowledge into daily life [17-19].

Although several advances and good results have been reported, the challenges concerning the use of wearable-device-based systems to real-time, remote, and daily control electroencephalographic patterns still need to be overcome.

The aims of our paper can be summarized as follow:

-to present a wearable wireless device-based system for real-time and remote EEG monitoring and to describe the proposed system modules as well as the signal processing algorithms;

-to explore the functionalities of this wearable EEG solution and to demonstrate its validity and robustness;

-to suggest its potential in the ability to increase the ease and flexibility of daily brain data recordings in the home environment.

The described approach, focusing on the emerging area of remote monitoring sensors and wearable devices applications, might be leveraged to measure, continuously display, and real-time monitor complex health outcomes in non-specialist and remote settings.

The paper is organized as follows: section 1.1 introduces the technical basis of EEG measurements; section 2 describes the architecture of the proposed monitoring system; section 3 presents the main steps of the test measurements, whereas section 4 reports the preliminary results. Finally, section 5 offers a discussion, and section 6 concludes the paper.

1.1. EEG Measurement Background: Technical Basis

The EEG records the electrical potentials of the scalp produced by the electrical activity of groups of neural cells. The electroencephalogram has an excellent temporal resolution (some tens of ms), while the spatial resolution (about one cm) could be better for the invasive signal acquisition methods [20]. In addition, the EEG is portable, inexpensive, and easy to set up; in fact, the electrodes can be placed on the scalp simply by wearing a headset.

The minimum configuration for EEG acquisition consists of three electrodes (ground and two recording electrodes). The grounding electrode placed on the scalp, nose, or neck provides a reference voltage for the amplifier. The two recording electrodes allow meas-urement of the potential of the scalp (all EEG recordings measure the potential difference between two electrodes). Typically, one of the two electrodes is designated as the recording electrode, and the other is defined as the reference electrode. Therefore, an electrode's posi-tion is chosen as the reference position in acquiring EEG signals. The electrode potentials in all other sites are recorded concerning the reference, exploiting the properties of the dif-ferential amplifiers. The reference can be positioned on earlobes or mastoids.

Generally, the electrodes are made of silver chloride (AgCl). The contact impedance between the electrode and the scalp should be between 1KΩ and 10KΩ to accurately rec-ord the signals. An EEG gel can be used between the electrode and the skin (wet electrodes); electrodes that do not need to use gel are called dry electrodes and are made of other materials such as titanium and stainless steel.

The International Federation of Electroencephalography and Clinical Neurophysiology has developed the International 10-20 System (Figure 1) for electrode placement [21]. This system uses two reference points on the head: "inion" (prominence at the base of the occipital bone) and "nasion" (located in the upper part of the nose at the same level as the eyes). The letter in each position indicates the specific region of the brain: A represents the earlobe, C is the central region, Pg is nasopharyngeal, P is the parietal, F is frontal, Fp is the frontal polar, and O the occipital area. The numbers identify the hemisphere: the odd numbers (1, 3, 5, and 7) refer to the left side and the even numbers (2, 4, 6, and 8) refer to the right side. The letter Z refers to the position on the midline. The 10-10 and 10-5 systems can be used for high-resolution EEG measurements, which are extensions of the interna-tional 10-20 system.

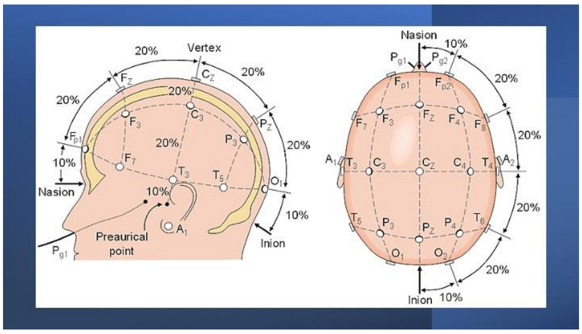

Figure 1. The international 10-20 system

The basic parameters of the EEG are the frequency (measured in Hz) and amplitude (measured in μV) of the EEG waves [22]. Generally, the rhythmic activity of the EEG varies according to the person's age and state of consciousness. The EEG consists of several rhythms classified according to frequency; these frequency bands, starting from the lowest to the highest, are indicated as delta (δ), theta (θ), alpha (α), mu (μ), beta (β) and gamma (γ) (Table 1).

The EEG signals recorded by the scalp through the electrodes are characterized by a low amplitude (of the order of a few microvolts); therefore, it is necessary to use an ampli-fication and conditioning front-end, both to increase the amplitude of the recorded signals through suitable amplification stages and to filter unwanted low or high-frequency com-ponents, to pass only the desired frequency band through the use of appropriate filters. Therefore, this front end is the most important unit in an EEG recording system because it cleans the EEG signal before converting it to digital. Generally, the signal is amplified about ten thousand times; a high-pass filter with a cut-off frequency of about 0.5 Hz is also used for the low-frequency components or to eliminate the direct component due to the polarization of the electrodes; a low-pass filter with a cut-off frequency of about 50-70 Hz for the higher frequency components and a notch filter to eliminate the 50 Hz component due to the power supply [23-24]. The sampling rates commonly used for EEG acquisitions are 100, 250, 500, 1000, and 2000 samples / s.

2. System Description

In this study, a wearable device-based EEG approach is proposed. It is analyzed as an integrative module of our SIMpLE system for remote health monitoring [25-26]. Indeed, our group recently presented the design and implementation of an innovative medical mobile cloud-based system named SIMpLE [25-27], which aimed to improve the monitoring of disease complications in patients

Table 1. EEG rhythms characteristics

Rhythm	Frequency	Amplitude	State
Rhythm δ	1-4 Hz	<200 μV	It is physiological in children and sleep states but can be detected in awake adults in the case of neurological diseases.
Rhythm θ	5-7 Hz	<100 μV	It is physiological in young children, older children, and adults in drowsy, meditative, or sleeping states but can be detected in awake adults in the case of neurological diseases.
Rhythm α	8-14 Hz	20-50 μV	It appears when an individual closes his eyes and relaxes; it disappears when the subject opens their eyes, makes a mental effort, or hears a sudden noise. Generally, these rhythms reflect visual processing and may also be related to brain memory function.
Rhythm μ	8-12 Hz	<80 μV.	It is strongly correlated to motor activities Additionally, the rhythm is attenuated by performing or imagining a movement or in response to tactile stimuli.
Rhythm β	15-30 Hz	5-20 μV	Like the μ rhythm, it is associated with motor activities. Appears in conditions of wakefulness, anxious thinking or active concentration. As for rhythm, the μ is attenuated by the execution or imagination of a movement or in response to tactile stimuli.
Rhythm γ	30-100 Hz	<10 μV	Its presence is associated with some motor functions or perceptions.

affected by neurodegenerative diseases, such as ALS patients and the elderly. The SIMpLE platform can be seen as an aid and support tool for the medical team as it can allow monitoring the patient's health conditions at a distance and eventually remotely intervene directly on the electronic instrumentation. As accurately described in the related paper, the SIMpLE system general architecture consists of three main modules (Figure 2): (i) data acquisition module, represented by commercial sensors nodes able to acquire physiological signals (i.e., EMG, ECG, and EEG signals) and other vital parameters, (ii) SIMpLE mobile, a sort of hub to send the acquired signals to the web-based system; (iii) the SIMpLE cloud-based system which includes: the patient summary management services (personal data, pathologies, clinical exams), the remote control, the visualization and the analysis of acquired signals, the management of patient diagnostic imaging and the teleconsultation subsystem. In this paper, the functionalities of the proposed wearable EEG solution were explored as an integrative module of the more sophisticated and secure medical platform SIMpLE [25-27].

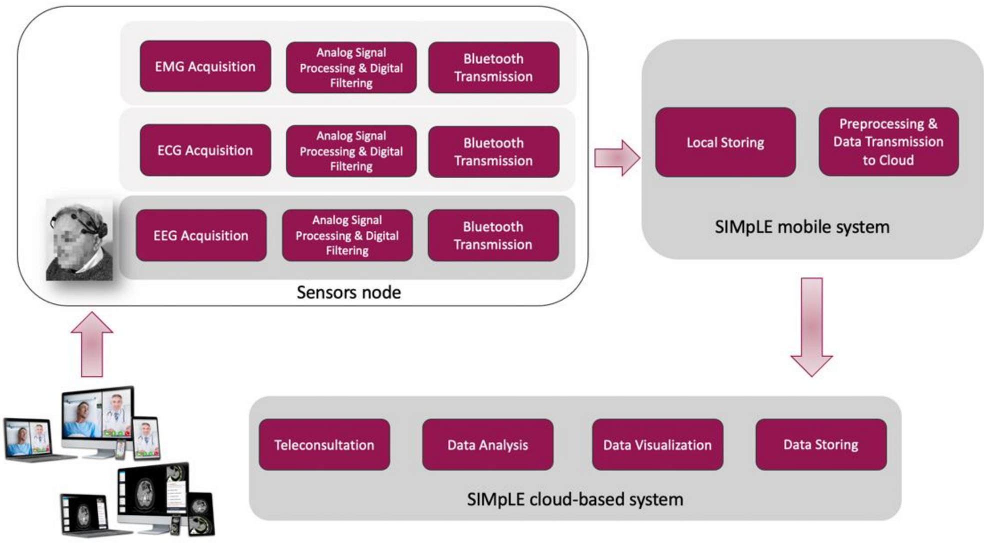

Figure 2. Constitutive modules of the SIMpLE system architecture. The EEG data acquisition sub-node is highlighted as an integrative module of a remote health monitoring system

2.1. Data Acquisition Unit: the EEG Measuring Instrumentation

In the Brain Computer Interface scenario and according to the producing company's reports, among recommended EEG, the Emotiv systems Inc. (San Francisco, USA) Epoc+ [28] plays an important role since it provides access to professional-grade brain data with a quick and easy to use design. Epoc+ is one of the most cost-effective mobile EEG Brain-wear® devices in the market that has been shown to provide data comparable to re-search-grade equipment, even in real-world settings [9-10]. The Emotiv Epoc+ is a portable, high-resolution, 14-channel, wireless EEG system designed to be easy to fit and take measurements in practical research applications. In this study, the Epoc+ (v 1.1) [28] headset is used. It presents a structure with two electrode arms, each containing 9 locations (7 sensors + 2 references) (Figure 3). Two sensor locations (Auxiliary Driven Right Leg (Aux DRL (M1)) / Auxiliary Common Mode Sense (Aux CMS (M2))) already have rubber sensors fitted because they are the alternative positions for the default references (CMS (P3) / DRL (P4)) [28]. M1 has the function of a ground reference point to measure the voltage of the other sensors, and M2 is considered a feed-forward reference point to reduce electrical interference from external sources. The 14 saline-based electrodes located at the positions AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4, according to the International 10-20 system, were identified with labels of the channels corresponding to the cerebral cortex region. They allow good coverage of the frontal lobes 'F' (involved in thoughts/conscious, deliberated movements) and also provide coverage of the temporal lobes 'T' (involved in speech reception), parietal lobes (sensory signal reception), and occipital lobes (signal reception from eye retinas). The technical specifications of the Emotiv Epoc+ are shown in Table 2.

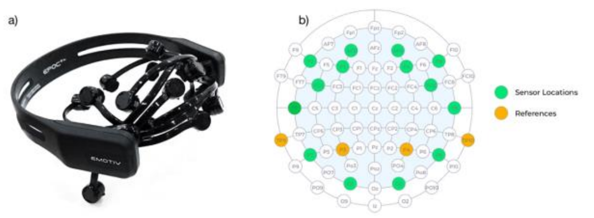

Figure 3. a) EPOC+ headset and b) sensor locations using the international 10-20 system

Table 2. Emotiv Epoc+ technical specifications

Headset Version	EPOC+ v1.1
Number of Channels	14 (plus CMS/DRL references, P3/P4 locations)
Channel names (International 10-20 locations)	AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4
Sampling Method	Sequential sampling. Single ADC
Sampling Rate	128 SPS / 256 SPS (2048 Hz internal)
EEG Resolution	14 bits with 1 LSB = 0.51μV (16 bit ADC, 2 bits instrumental noise floor is discarded)
Bandwidth	0.2 - 45Hz, digital notch filters at 50Hz and 60Hz
Filtering	Built-in digital 5th order Sinc filter
Dynamic Range (input referred)	8400 uV(pp)
Coupling Mode	AC coupled
Connectivity	Proprietary 2.4GHz wireless, BLE and USB (Extender only)
Battery Capacity	LiPo battery 680mAh
Battery Life (typical)	12 hours
Impedance Measurement	Real-time contact quality using patented system
IMU Part	LSM9DS0
Accelerometer	3-axis +/-8g
Gyroscope	3-axis +/- 500 dps
Magnetometer	3-axis +/- 12 gauss
Motion Sampling	32 / 64 / 128 Hz (User Defined)
Motion Resolution	14 / 16-bit (User Defined)
Sensor Material	Ag/AgCl + Felt + Saline

The potential of remote monitoring using sensors, wearable and mobile solutions to measure brain electrical activity directly was discussed in an in-depth article [6]. In this study, several innovations related to brain monitoring devices were reviewed. Within the portable EEG headband class type, the Emotiv Epoc+ was listed as a remote-monitoring device, and its applicability in clinical trials was investigated.

The Emotiv Epoc has been given the most attention in the literature compared to other wireless EEG systems [9-10, 30-35].

In terms of signal quality, several rigorous evaluation experiments must be carried out to prove that the EEG data collected by a specific device can be reliably used in research or daily life. Wang *et al.* [36] tested the validity of the P300 signal measured with the Emotiv Epoc+ system by comparing the P300 waveforms recorded with a medical-grade EEG system, the G.TEC g. USBamp device [37]. The results revealed that both N200 and P300 Event-Related Potential (ERP) waveforms produced by the Epoc+ system were similar to those produced by the G.TEC system, confirming that Emotiv Epoc+ can produce useful ERP waveforms. Similarly, Stytsenko *et al.* [32] compared the Emotiv Epoc and G.TEC systems, confirming that both systems are alike. Dadebayev *et al.* [38] demonstrated that low-cost consumer-grade EEG devices, including Emotiv Epoc+, can perform equally well as research-grade devices.

In terms of price, Emotiv Epoc+ is much less expensive compared to g.USBAMP, for example, the most popular clinically-approved, professional EEG system from G.TEC company, or to g. Nautilus RESEARCH, a G.TEC wearable EEG headset.

Concerning the ergonomic aspect, Emotiv Epoc does not need a flexible EEG cap. Therefore, it does not require custom fitting; also, due to its form factor, it would allow longer subject screening [39].

In addition to the regular 14 EEG electrodes, Epoc+ offers another nine inbuilt motion electrodes, such as a gyroscope, accelerometer, and magnetometer, each type having three sensors. This enables users to track the actual changes in the position more clearly, even during very complex motions [38].

Moreover, Epoc hi-performance wireless gives users a total range of motion. Indeed, Epoc+ transmits wireless data at 128 or 256 Hz, so it can record high-resolution brain data outside of the laboratory and without being tethered to a computer.

Overall, the choice of Emotiv Epoc is justified as it presents several advantages: high signal quality, fewer artifacts, 14 sensors, ready-to-use assembly, modern design, and low price. The disadvantages of the Emotiv Epoc device are being non-dry sensors and requiring raw data access licenses.

2.1.1. Data Transmission Unit

The Epoc universal USB receiver uses a proprietary 2.4GHz protocol to stream data from the headset. This solution is recommended in an environment with high levels of Bluetooth interference. The alternative is to use Bluetooth Low Energy (BLE 4.0). In this study, the electroencephalographic signals are gathered using the Emotiv Epoc+ headset and transferred via Bluetooth to a computer for accurate time visualization and offline local processing. In addition, it is possible to use a previously described SIMpLE mobile approach [25-27], a sort of hub through which the acquired signals are sent to the web-based system.

2.2. EEG Data Processing and Monitoring Unit

2.2.1. Real-Time EEG Data Acquisition and Visualization

The Emotiv Epoc+ system is wireless and connect to the computer through EmotivPRO software using either an USB Receiver Dongle or the native Bluetooth adapter (See Table 2 for headset details). EmotivPRO (version 2.6.3.305) [29], an easy-to-use and efficient toolkit, is used to acquire and analyze EEG data all in one integrated software environment. EmotivPRO allows visual-ization data streams in real-time whenever the headset is connected. The raw EEG section displays the voltage fluctuations (as uV per sample) detected from each sensor on the headset (14 channels for Epoc+).

In addition, the motion tab displays a real-time data stream from the headset's digital motion sensors (4 quaternions, 3 accelerometers, and 3 magnetometers). It also allows controlling the data packet stream, showing the number of data packets success-fully transferred from the headset to the PC and those dropped.

2.2.2. Offline Data Analysis

EmotivPRO stores EEG and motion data in a standard format compatible with many EEG analysis programs. A JSON (JavaScript Object Notation) file is also generated, containing the descriptions of the keystroke markers used and their corresponding values in the stored acquisition files. The data is then exported and prepared for offline analysis, described in Section 3.1.4.

3. Materials and Methods

3.1. Test Measurements

Several studies investigated the performance of mobile and wearable consumer-grade EEG devices compared to a clinical gold standard [3, 9-11]. Indeed, research shows that mobile systems can reproduce findings derived from traditional EEG (providing support for construct validity) [e.g., 30]. At the same time, some studies directly compared the data acquired by mobile versus traditional systems (providing support for criterion validity) [e.g., 31]. Despite this scientific evidence, in this section, we aimed to demonstrate the validity of the Emotiv Epoc+ device in the continuous, real-time, and remote acquisition and monitoring of electroencephalographic signals.

3.1.1. Participants

The selected participant to test the Epoc+ device during the resting state paradigm is a healthy control subject (gender: male, age: 70) with no neurological disorders who voluntarily agreed to become a research resource. The experiment was performed after obtaining written consent.

3.1.2. Task Design

The Emotiv Epoc+ system was used to collect EEG data across 14 channels during a well-established resting state paradigm in which participants sat quietly with their eyes open and then closed for 3 min each [39] (Figure 4). More specifically, during the first trial condition (eyes open), subjects were instructed to sit quietly and gaze at a black fixation cross against a grey (RGB values 160, 160, 160) background, while during the second one (eyes closed) to remain to sit quietly but with their eyes closed until they heard a tone (which indicated the end of the trial). Each trial condition lasted 3 min.

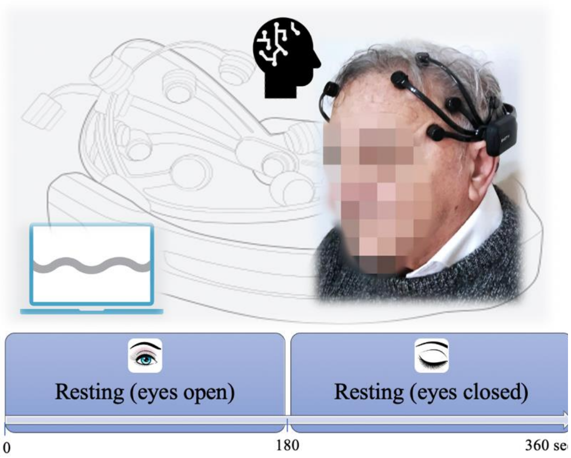

Figure 4. The wearable device on the subject (upper panel) and the experimental task design (bottom panel)

3.1.3. Procedure

EEG patterns were acquired using the EMOTIV Epoc+ headset in a quiet, silent room. Each electrode is held with a plastic arm equipped with a small cap with a saline-soaked felt pad inside. To increase the conductance of 14 wet electrodes, a multipurpose contact lens solution was used, as the company suggested.

The experimental procedure includes the following phases (Figure 5):

-*Phase 1:* as recommended, the sensors were hydrated in the provided hydrator pack with contact lens saline solution. The felt pads must be fully saturated with a solution to achieve good contact. Each sensor unit was removed from the hydrator pack and inserted into the black plastic headset arms.

-*Phase 2:* the headset was placed onto the subject's head, making sure that the reference sensors with black rubber covering were positioned on the bone just behind each ear lobe. Furthermore, for a correct fitting of the headset, the two front sensors must be at a distance of about three fingers above the eyebrows.

-*Phase 3:* the Epoc+ device is paired via Bluetooth (BLE 4.0) and connected to EmotivPRO. The EEG quality indicator on the EmotivPRO software was used to verify the overall EEG quality averaged across all the sensors. Using a saline liquid decreased electrode impedance until the level required by the software was reached (in the 10–20 k Ω range).

The contact status for each sensor was checked in real-time and adjusted (if needed) during the experiment to achieve 100% contact quality (in Figure 5, the green color indicates good EEG quality).

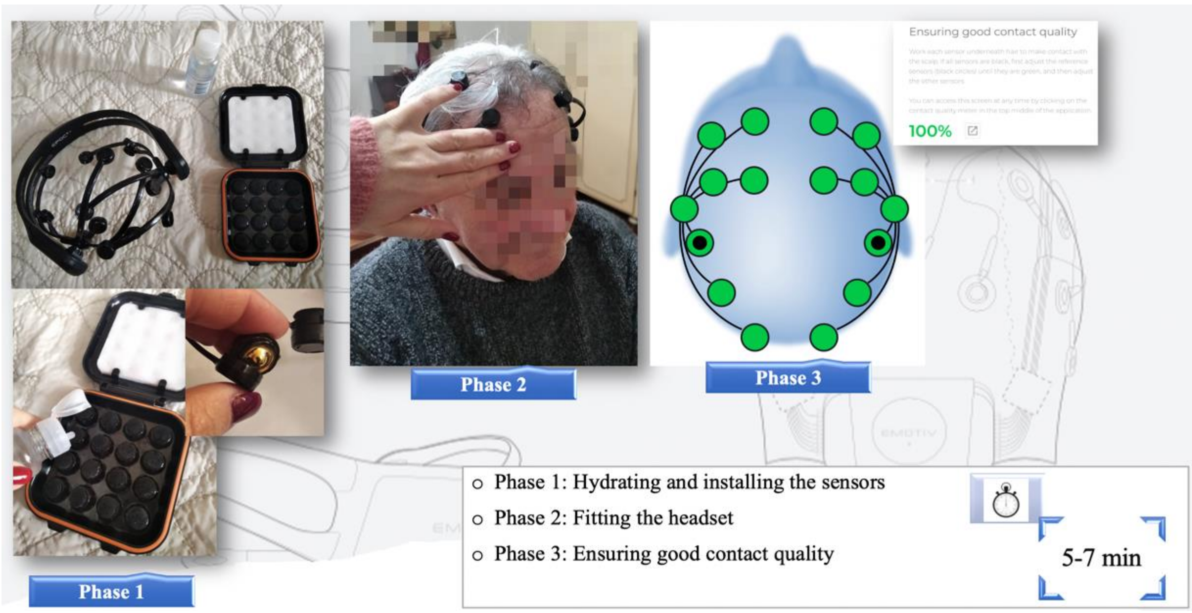

Figure 5. Experimental procedure phases

To set up the headset for the subject and complete the signal quality check, it took 5 to 7 minutes. This feature confirms the chosen device's applicability in real-time monitoring, telemedicine, and remote control. The subject was instructed to stay still while capturing EEG patterns to reduce head motion artifacts.

3.1.4. Offline EEG Data Analysis Pipeline

All EEG data were processed following the analysis pipeline reported in [39] using MATLAB (MAtrix LABoratory, The MathWorks, Inc., Natick, MA, USA) and EEGLAB [40]. MATLAB (version 2019.0) and Fieldtrip (version 20190819) [41] were adopted to perform spectrum analysis on resting state data.

More specifically, the raw EEG data was loaded in EEGLAB considering the total acquisition (3 min eyes open and 3 min eyes closed), and the Epoc+ channels configuration was imported as a .ced file. After DC offset removal, the resting EEG data were bandpass filtered from 0.1 to 30 Hz.

Automatic artifact detection and continuous data correction were performed using Artifact Subspace Reconstruction (ASR) [42-43], available as part of the open-source EEGLAB plugin clean raw data [44].

The Clean Rawdata plug-in (version 2.0) interface is the default EEGLAB method for removing artifacts from EEG signals, allowing detection and separating low-frequency drifts, flatlines, and noisy channels from the data.

It can also use methods such as automated subspace removal to identify, reject or remove 'artifacts' (high-amplitude non-brain activity produced by eye blinks, muscle activity, sensor motion, etc.) by comparing its structure to that of known artifact-free reference data [44-45].

After filtering, automatic artifact detection/data correction, and re-referencing to the common average, the data were trimmed into eyes-open and eyes-closed trials and prepared for paradigm-specific processing.

Following the resting state data processing pipeline described in [39], two spectral analyses were performed using a 5 s, non-overlapping Hanning window in 0.2 Hz steps in Fieldtrip (‘ft_freqanalysis’ function with length = ‘5’, method = ‘mtmfft,’ and taper = ‘hanning’ arguments).

The first analysis was carried out on frequencies from 1 to 30 Hz in 1 Hz bins, while the second was conducted on alpha band (8–12 Hz) frequencies only in 0.004 Hz bins. Finally, an alpha band power scalp topography map was created with Fieldtrip using the‘ft_topoplotER’ function, which displays ERP data as a spatial topography in a specified latency window.

4. Results

EmotivPRO allows to visualize the raw EEG (the voltage fluctuations) detected from each sensor on the headset.

Figure 6 shows raw EEG graphs, displayed as uV per sample, for all 14 channels during the resting state protocol (eyes open (before pink line marker) and eyes closed (after pink line marker) conditions), for the healthy subject. A 0.16Hz high-pass filter is activatedby default from EmotivPRO software to remove the DC offset.

As results of the spectral analysis conducted on alpha band (8–12 Hz) frequencies, the topographical alpha power distributions for eyes-open and eyes-closed resting state conditions are depicted in Figure 7.

In addition, the results from the spectral analysis carried out on frequencies from 1 to 30 Hz are presented in Figure 8. It shows contrast power for each condition across channels on the occipital region involved in the resting state paradigm (Figure 8A). More specifically, power spectrum comparison between ‘eyes open’ and ‘eyes closed’ conditions across frequencies (1–30 Hz) over channel O_1 (left hemisphere) (Figure 8B)) and channel O_2 (right hemisphere) (Figure 8C)), is presented.

5. Discussion

The number of consumer-grade EEG devices in the current market has increased dramatically over the past decade. The scientific community is focused on proving the validity of these products in terms of the quality and reliability of the acquired EEG data, thus demonstrating its efficacy in clinical and daily life applications [6, 8, 30]. In particular, several rigorous evaluation experiments have been carried out to prove that the EEG data collected by the Emotiv Epoc+ device can be reliably used in daily life, as it can perform equally well as research-grade devices [9-10, 31, 32-35].

Our research group has been focused for years on biosignals acquisition and processing methodologies and approaches, mainly applied in the context of innovative technological solutions and assistive systems designed to preserve communication and inter-action with the external world in people with ALS [25-27, 46-49].

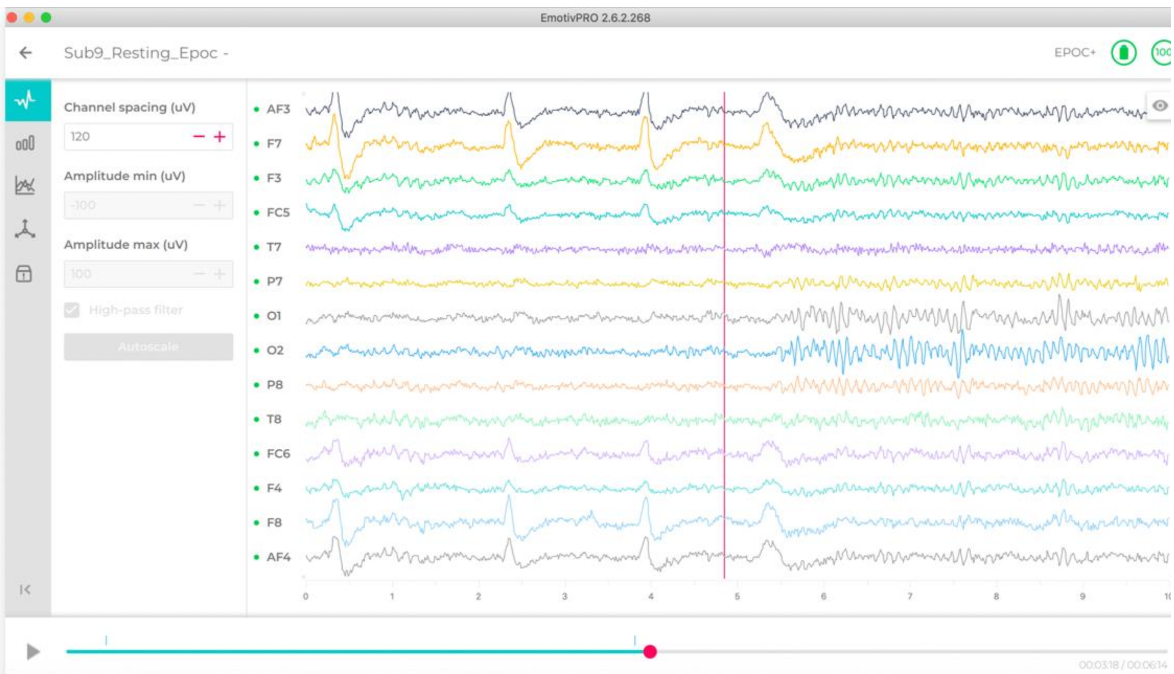

Figure 6. Raw EEG graphs for all 14 channels for eyes-open (before pink line marker) and eyes-closed (after pink line marker) conditions

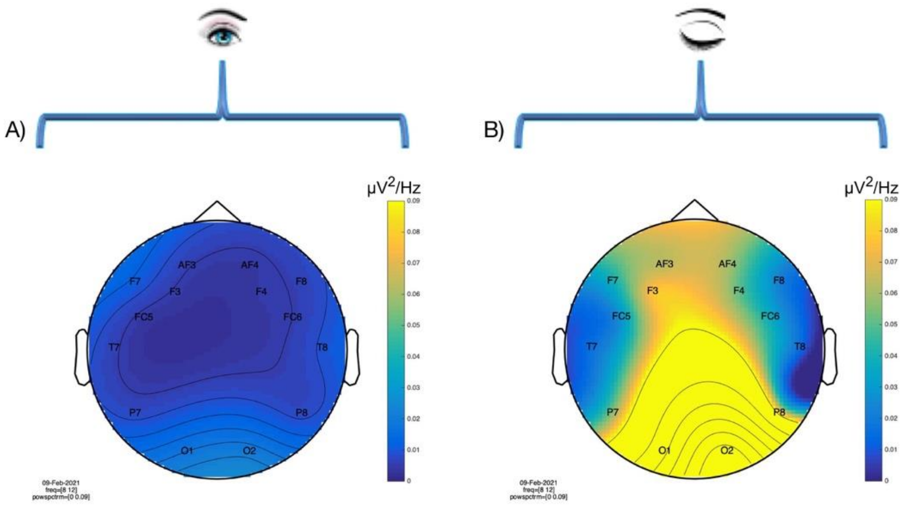

Figure 7. Scalp topography maps on alpha power (8–12 Hz) for eyes-open A) and eyes-closed B) conditions

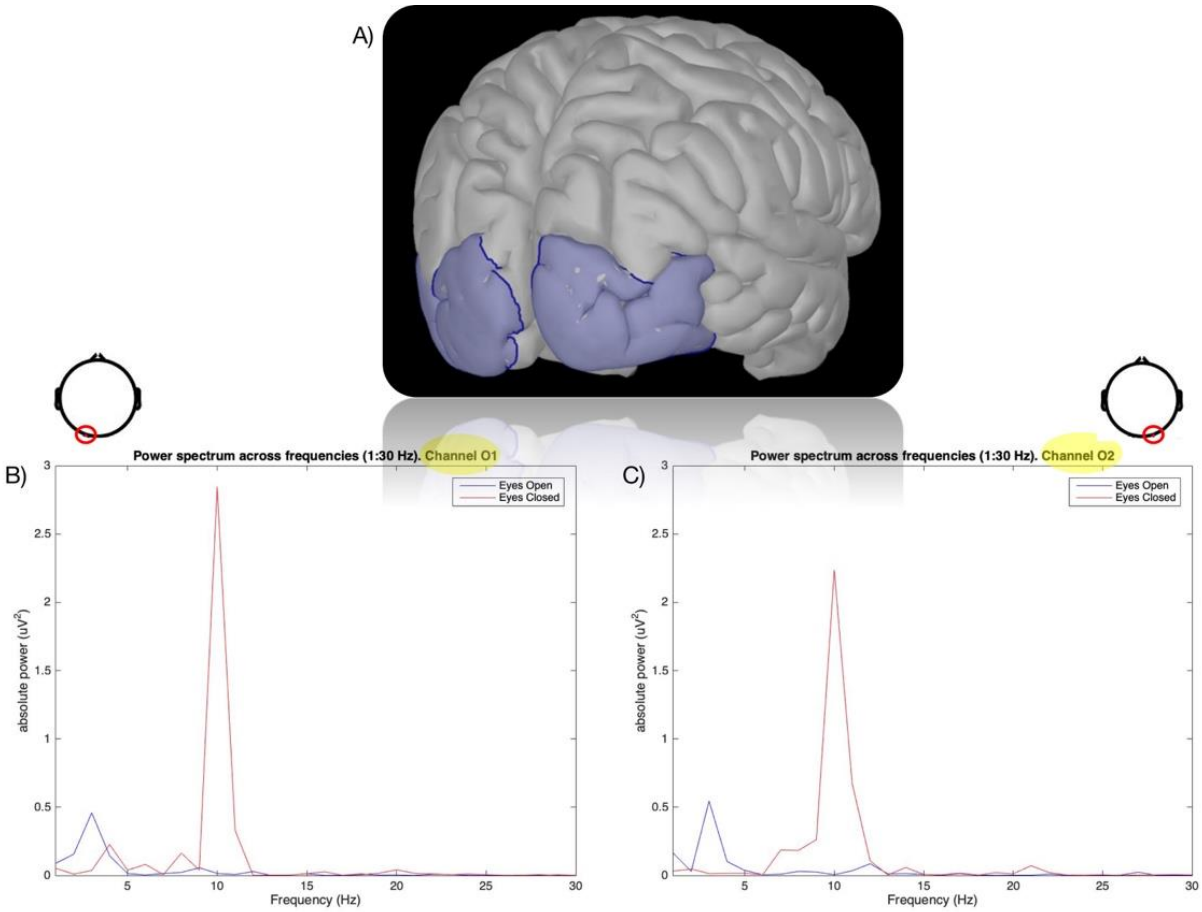

Figure 8. A) Occipital region involved in the resting state paradigm. B) Power spectrum comparison between 'eyes-open' and 'eyes-closed' conditions across frequencies (1–30 Hz) over channel O1 (left hemisphere) and C) channel O2 (right hemisphere)

Our paper aims not only to present a wearable device-based system for real-time EEG monitoring, to describe the proposed system modules and the signal processing algorithms, but also to suggest its potential role in measuring complex health outcomes in non-specialist and remote settings. Our findings confirmed the Epoc+ reliability for event-related brain potential research and in measuring acceptable spectral EEG data. This is supported by the evidence that real-time raw EEG graph and offline spectral analyses results showed higher alpha power during eyes-closed relative to eyes-open conditions (Figure 6-7-8). In addition, we suggested the potential of our mobile and wearable EEG system to increase the ease and flexibility of daily brain data recordings in the home environment. Indeed, conceiving the described wearable device-based EEG approach as an integrative module of a more complex cloud-based SIMpLE system for remote health monitoring [8], it is possible to take advantage of its precious functionalities. More specifically, the cloud-based SIMpLE system allows: management of patients' data, storing and visualizing bio-signals acquisitions as well as patients' DICOM (Digital Imaging and Communications in Medicine) images, and the use of the teleconsultation interface [25].

The potential of our mobile and wearable EEG system, seen as an integrative module of the SIMpLE platform, resides in the ability to increase the ease and flexibility of daily brain data recordings in the home environment. Indeed, it can be seen as an aid and support tool for the medical team as it can allow monitoring the patient's health conditions at a distance and eventually remotely intervene directly on the electronic instrumentation.

Although the described system has all the features to be used in remote health monitoring, it needs further improvements. First, the system validation procedure requires many EEG acquisitions on control and pathological subjects to confirm its robustness. Other important suggestions concerning the influencing factors (battery life, signal quality, and stability (wireless connectivity), for example) that affect the performance of wire-less EEG systems need to be discussed.

Considering that wireless EEG devices are generally battery-operated, they are subject to potential loss of data when the battery charge falls below a specific threshold level. Ensuring that batteries are charged and operational throughout long studies can be difficult, and it will increase the complexity of data-gathering using EEG devices.

The research focused on a long-term study of brain activities should try to rely on less sensory information [50].

The Emotiv Epoc+ has an excellent battery life of 12 hrs. enabling the headset to be worn throughout a normal working day [17, 51].

As for the second aspect, during the capture of brain data, the headset can lose its wireless connectivity and not record the data. Although this represents one of the major drawbacks of wireless EEG headsets, EmotivPRO presents a data packet display module. It allows evaluation of the number of data packets successfully transferred from the head-set's sensors to the computer. This is an important aspect of verifying data integrity for wireless transmission links.

Another important aspect is that, although EEG wearables allow for more mobility, they are highly sensitive to movement artifacts. There is, therefore, an urgent demand for advanced machine-learning algorithms suitable to detect and correct a wide variety of artifacts in real time while maintaining the signal of interest.

6. Conclusion

In recent years, in the context of EEG, a new trend is spreading focused on incorporating real-time neural pattern recording into consumer-oriented applications and providing a highly portable solution suitable for collecting frequent data from patients in remote settings, such as the home [6].

Portable and wearable solutions, as well as the opportunity for real-time and continuous mobile EEG recording, promise to translate neuroscientific knowledge into clinical and daily life applications. Indeed, the opportunity to efficiently perform repeated recording at home could lead to a "patient-controlled home EEG monitoring" model, which has two advantages: to increase the accuracy of diagnosis and reduce requirements for hospital-based monitoring.

The aims of our paper can be summarized as follow:

-to present a wearable device-based system for real-time and remote EEG monitoring and to describe the proposed system modules and the signal processing algorithms;

-to explore the functionalities of this wearable EEG solution and to demonstrate its validity and robustness;

-to suggest its potential in the ability to increase the ease and flexibility of daily brain data recordings in the home environment.

Our findings confirmed the Epoc+ reliability for event-related brain potential (ERP) research and in measuring acceptable spectral EEG data.

The described approach, focusing on the emerging area of remote monitoring sensors and wearable devices applications, might be leveraged to measure, continuously display, and real-time monitor complex health outcomes in non-specialist and remote settings.

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