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Proceeding Paper

From In-Ear Canal to Neural Dynamics–Electroencephalography for Everyday Brain Sensing †

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Abstract

This paper describes the development and testing of a portable in-ear electroencephalography (EEG) system that uses dry electrodes made from different materials. Brain signals were collected from electrodes placed inside the ear and around the ear and were compared with signals recorded using standard scalp EEG systems. The results indicate that EEG signals recorded from the ear show a clear correlation with those obtained from scalp electrodes. At the same time, the in-ear system provides better user comfort, fewer movement-related artifacts, and a more discreet form factor. Even though the signal-to-noise ratio is slightly lower than in conventional EEG systems, the device remains suitable for portable and long-term recordings. These findings confirm that in-ear-EEG technology is a viable solution for applications in audiology, neuroscience, clinical brain monitoring, and brain–computer interface systems.

Keywords: dry electrodes; EEG signal; EEG electrodes; in-ear-EEG; portable device; signal processing

1. Introduction

Electroencephalography (EEG) is an important method used in medicine and neuroscience to study brain activity. It is commonly applied in the diagnosis and monitoring of neurological disorders and in the development of brain–computer interface systems. However, traditional EEG equipment usually requires many electrodes placed on the scalp, long preparation time, and trained personnel. These aspects make classical EEG systems uncomfortable and difficult to use for mobile or long-term monitoring [1].

To overcome these limitations, recent research has focused on alternative EEG recording methods that improve comfort and usability. One of these approaches is in-ear EEG, where electrodes are positioned inside or around the ear. In-ear-EEG systems are smaller, easier to wear, and less visible, which makes them more suitable for daily life use and recordings outside clinical environments.

Several studies have shown that in-ear-EEG can provide meaningful information about brain activity. A review by Kaongoen et al. [2] highlights recent progress in in-ear-EEG technology, including improvements in electrode materials, sensor design, and application

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areas. In addition, Juez et al. [3] report that in-ear-EEG has been successfully used in multiple domains, such as evoked potential analysis, sleep monitoring, epilepsy detection, and brain–computer interfaces.

Despite these advantages, in-ear-EEG systems still face challenges related to signal quality. Recordings can be affected by artifacts, especially those caused by eye movements and head motion. Yarici et al. [4] analyzed the influence of ocular artifacts on in-ear-EEG signals and showed that, although such artifacts are present, in-ear-EEG remains sensitive to brain activity from temporal regions.

Comparing in-ear-EEG with conventional scalp EEG is essential for evaluating its practical usefulness. Moumane et al. [5] demonstrated that signals recorded from the ear are correlated with scalp EEG signals, even if the signal-to-noise ratio is slightly lower. However, in-ear-EEG offers better stability during movement and improved comfort for the user.

The goal of this paper is to design and evaluate a minimally invasive in-ear-EEG device using dry electrodes made from different materials. The study investigates signal quality, recording stability, and user comfort, with the aim of assessing the suitability of ear-EEG systems for portable and long-term brain monitoring applications.

2. Methodology

This section describes the methodology used for the design, implementation, and validation of ear-EEG acquisition systems. The approach includes the development of multiple recording devices, the evaluation of different dry electrode materials, the use of several EEG acquisition platforms, and the software tools applied for signal recording and analysis.

2.1. In-Ear-EEG Device Design and Electrode Placement

The aim of the device design was to obtain stable EEG recordings from the ear area while ensuring user comfort and ease of use. For this purpose, two independent ear-EEG devices were developed, each optimized for a specific electrode configuration.

2.1.1. Intra-Auricular Device Using Silver Electrodes

The first device was designed exclusively for intra-auricular EEG acquisition and uses silver dry electrodes. This prototype is shown in Figure 1. The device consists of an ergonomic in-ear component shaped to fit the ear canal and to ensure firm electrode–skin contact. The geometry of the device was optimized to minimize electrode movement during recordings, thereby reducing motion-related artifacts.

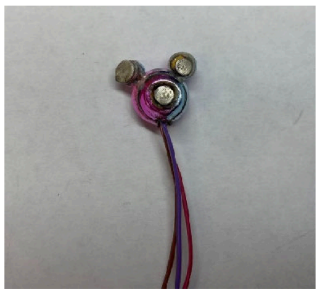

Figure 1. In-ear-EEG with silver electrodes.

This intra-auricular device does not include external supports or behind-the-ear components. Its design is focused on simplicity and stability, allowing EEG signals to be recorded directly from inside the ear canal. The compact structure improves comfort and makes the device suitable for prolonged recordings.

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The placement of the intra-auricular electrodes was selected in relation to the international 10–20 EEG system. Although the electrodes are positioned inside the ear, their locations correspond to nearby temporal scalp regions. The relation between intra-auricular electrode positions and standard scalp electrode locations is illustrated in Figure 2. This correspondence allows a meaningful comparison between in-ear-EEG and conventional scalp EEG recordings.

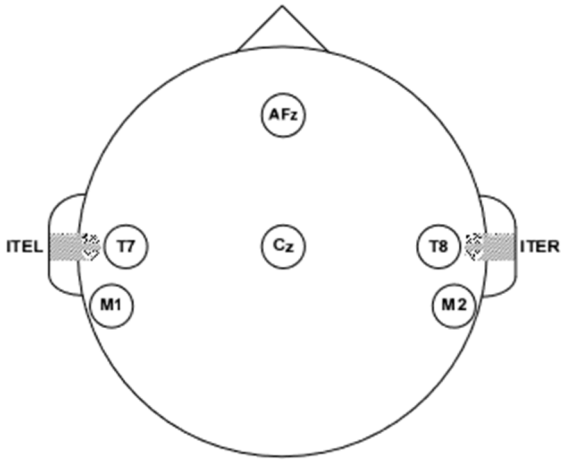


Figure 2. 10–20 systems position of intra-auricular and scalp electrodes.

2.1.2. Ear-Centered Device Using Gold Electrodes

A second, independent ear-centered device was developed for experiments using gold electrodes. This device is different from the intra-auricular silver prototype and includes both an in-ear component and an external support structure. The complete configuration of this device is shown in Figure 3.

Figure 3. Ear-EEG signal acquisition device using gold electrodes.

2.2. Dry Electrode Materials

To evaluate the influence of electrode material on EEG signal quality, three types of dry electrodes were tested: silver electrodes, flexible polymer electrodes, and gold electrodes.

2.2.1. Silver Electrodes

Silver electrodes were selected for in-ear-EEG acquisition due to their high electrical conductivity, low impedance, and good electrochemical stability. These properties are important for recording low-amplitude EEG signals.

For this study, solid silver electrodes were used. These electrodes are composed of highly conductive elements such as silver, silver chloride, and copper, which ensure good electrical contact and reduce signal loss. The silver material was manually shaped to match the ear canal geometry, improving electrode–skin contact.

After shaping, the electrodes were integrated into an ergonomically designed in-ear housing. Shielded copper wires with low resistivity were used to connect the electrodes to

the EEG acquisition systems, minimizing electromagnetic interference. Electrical connections were made using tin-based solder alloys at controlled temperatures to preserve the properties of the materials.

To validate the performance of the silver electrodes, EEG signals were recorded using an OpenBCI Cyton Biosensing Board (OpenBCI, Brooklyn, NY, USA) [6] with eight channels and compared with signals obtained using the Ultracortex "Mark IV" EEG headset (OpenBCI, Brooklyn, NY, USA). The comparison showed improved stability and reduced motion artifacts for the intra-auricular silver electrodes.

2.2.2. Flexible Polymer Electrodes

Flexible polymer electrodes developed by OpenBCI, known as ThinkPulse™ active electrodes, were used for extra-auricular EEG recordings. These electrodes are designed to improve comfort due to their flexibility and biocompatibility.

The polymer electrodes were placed outside the ear, mainly in mastoid (M1, M2) and temporal (T7, T8) regions, as illustrated in Figure 2. Their flexible structure allows better adaptation to the skin surface, which improves comfort and electrode contact.

Analysis of the recorded signals showed that polymer electrodes produced higher signal amplitudes compared to intra-auricular electrodes. However, the noise level was also higher, leading to a signal-to-noise ratio similar to that obtained with intra-ear recordings. These results confirm the feasibility of extra-auricular EEG acquisition and demonstrate a correlation between ear-based and scalp EEG signals.

2.2.3. Gold Electrodes

Gold electrodes were tested due to their high conductivity, chemical stability, and excellent biocompatibility. Although gold electrodes are more rigid and more expensive than other materials, they provide stable and reliable EEG recordings.

The gold electrodes were mounted on the dedicated ear-centered device described earlier. One electrode was placed inside the ear canal to reduce movement-related noise, while two electrodes were positioned outside the ear, including a reference electrode. This configuration, shown in Figure 3, allowed stable signal acquisition and reduced artifacts during recordings.

2.3. EEG Signal Acquisition Hardware

To validate the authenticity and reliability of the EEG signals, three different acquisition systems were used. The first acquisition system was developed in the laboratory and is based on analog signal conditioning components. The system includes an AD620ANZ instrumentation amplifier (Analog Devices, Wilmington, MA, USA) for initial amplification, followed by TL074 operational amplifiers (Texas Instruments, Dallas, TX, USA) used for filtering and gain control. Resistors, capacitors, and a trim potentiometer were used to adjust amplification levels and filter characteristics. The circuit was powered by a 9 V supply and connected to an Arduino development board for signal digitization. The laboratory prototype is shown in Figure 4.

The second acquisition platform was the OpenBCI Cyton + Daisy Biosensing system (version Cyton + Daisy, OpenBCI Inc., Brooklyn, NY, USA), which supports up to 16 EEG channels. The system is based on the PIC32MX250F128B microcontroller (Microchip Technology Inc., Chandler, AZ, USA) and allows EEG, EMG, and ECG acquisition. Data are transmitted wirelessly to a computer using radio modules.

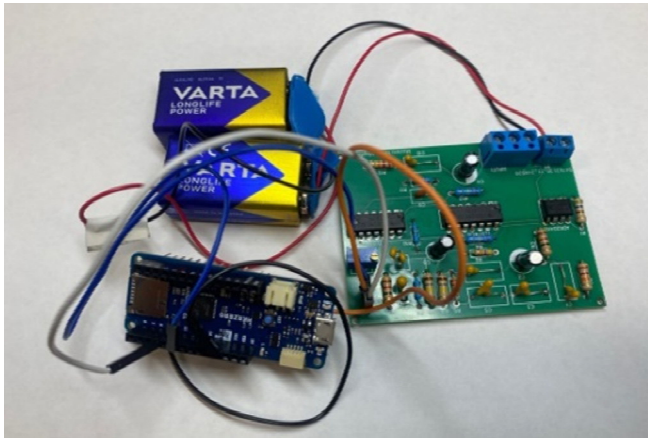


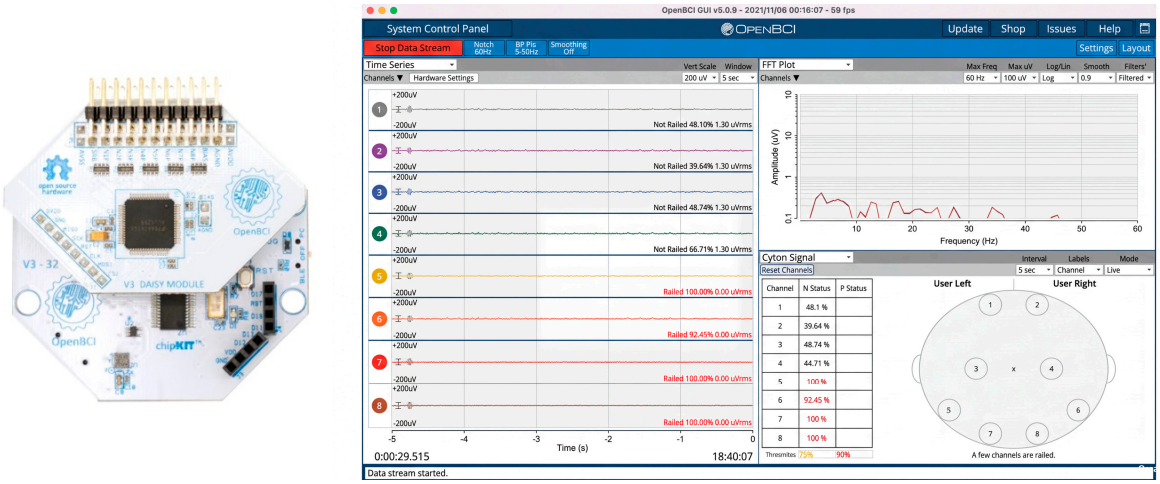
Figure 4. EEG acquisition system prototype.

The third acquisition system was based on the EEG Click module developed by Mikroe (MikroElektronika d.o.o., Belgrade, Serbia). This module uses the INA114 precision instrumentation amplifier (Texas Instruments Inc., Dallas, TX, USA) and the MCP609 operational amplifier (Microchip Technology Inc., Chandler, AZ, USA) for signal amplification and filtering. The system uses a three-electrode configuration and was connected to an Arduino MEGA2560 board (Arduino AG, Italy) through a MikroBUS Shield adapter (Mikroe, Belgrade, Serbia). The complete setup is shown in Figure 5.

Figure 5. EEGClick system.

2.4. Software Tools

EEG data acquisition and processing software depend on the hardware platform used. For OpenBCI-based recordings, the OpenBCI GUI (version 5.0.9, OpenBCI Inc., Brooklyn, NY, USA) was used for real-time visualization and monitoring. This software provides time-domain signal display, frequency analysis using Fast Fourier Transform (FFT), signal filtering, and multiple data export options. The Cyton + Daisy system is illustrated in Figure 6a. The user-mode interface of the OpenBCI GUI is shown in Figure 6b.



(**a**) (**b**)

Figure 6. (**a**) Cyton + Daisy Biosensing Boards, (**b**) OpenBCI GUI.

3. Signal Processing and Visualization Results

EEG signals were processed using Python Language (NumPy, SciPy) (Version 3.15.0a6) to analyze their temporal and frequency characteristics. The recorded data from two channels, one intra-auricular and one extra-auricular, were imported for offline analysis. The time-domain representation is shown in Figure 7. Both channels exhibit low-frequency electrode drift, 50 Hz powerline interference characteristic of unshielded prototype hardware, and intermittent transients consistent with ocular (EOG) and muscular (EMG) artifacts. The FFT spectrum confirms 50 Hz as the dominant spectral component, reflecting the absence of an active notch filter and driven right-leg (DRL) circuit in the current prototype iteration.

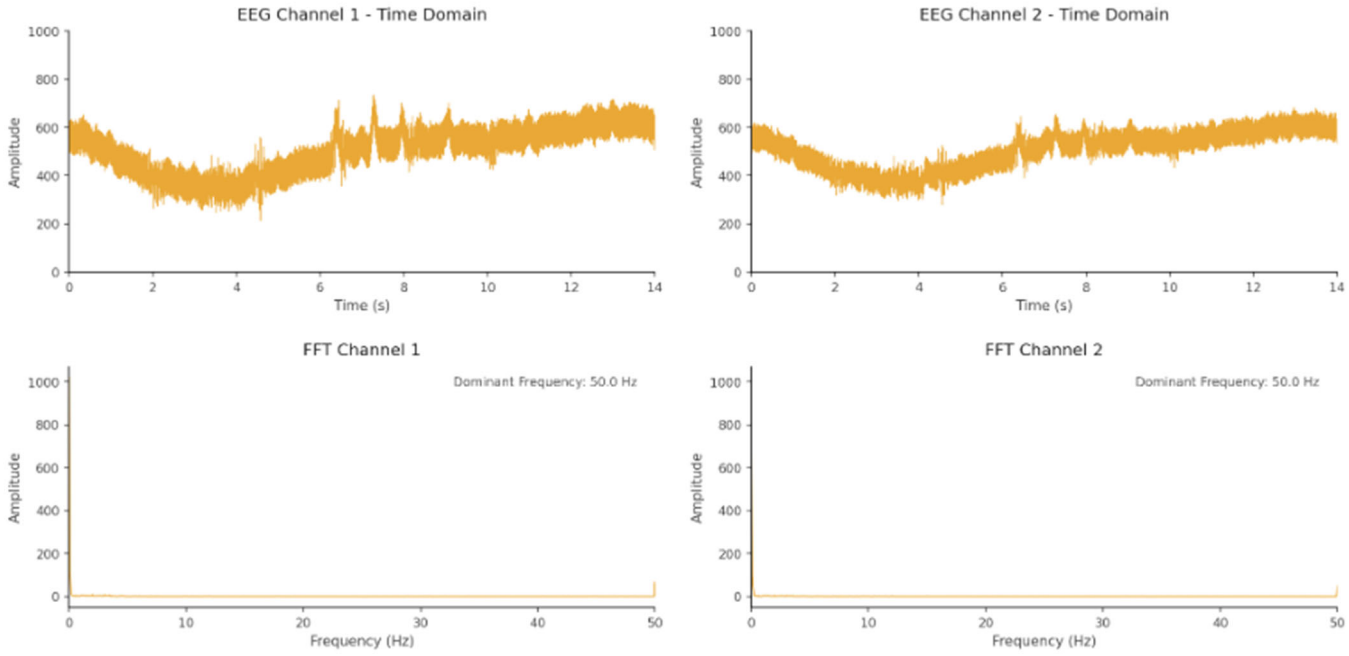


Figure 7. Signal analysis.

Frequency analysis was performed using the FFT. The frequency spectra presented in Figure 8 show a dominant component at approximately 50 Hz on both channels, consistent with powerline interference characteristic of unshielded prototype hardware operating without an active notch filter. Underlying EEG-band components (Delta, Theta, Alpha,

Beta) are present across the 0.5–30 Hz range but are partially obscured by this artifact source, which represents the primary limitation of the current prototype iteration.

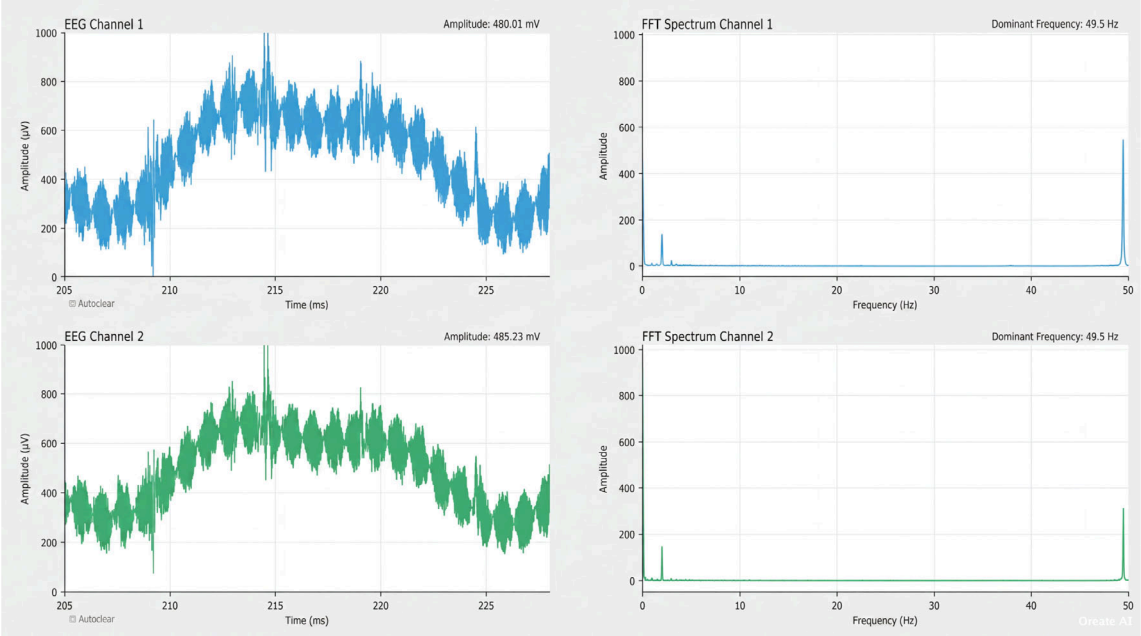


Figure 8. EEG monitoring application interface.

In addition to offline processing, a real-time EEG monitoring application was developed using web technologies. The graphical interface, illustrated in Figure 8, displays live EEG signals and their corresponding frequency spectra for both channels, enabling continuous data acquisition and visualization. Despite the hardware limitations identified above, the interface successfully demonstrates the feasibility of real-time signal acquisition and display outside specialized laboratory environments, providing a functional foundation for future hardware improvements.

The real-time visualization confirms that EEG data can be processed and displayed continuously outside specialized scientific software environments. The ability to adjust parameters such as sampling rate and time window during operation demonstrates the flexibility of the proposed monitoring system. These results highlight the feasibility of real-time EEG visualization for portable and user-friendly brain monitoring applications.

4. Conclusions

This study presented the design and evaluation of ear-centered EEG systems using dry electrodes made from different materials. The experimental results show that EEG signals recorded from the ear are correlated with conventional scalp EEG recordings and contain relevant temporal and frequency features.

The analysis demonstrated that intra-auricular electrodes provide stable recordings with reduced motion artifacts, while extra-auricular electrodes offer higher signal amplitudes but increased noise. Despite these differences, both recording methods allow the identification of characteristic EEG frequency bands.

Signal processing confirmed the presence of meaningful EEG components below 30–40 Hz. In addition, the developed web-based interface demonstrated the feasibility of real-time EEG monitoring and visualization outside specialized software platforms.

Overall, the results confirm that in-ear EEG is a practical and reliable solution for portable and long-term brain activity monitoring, with potential applications in neuroscience research, clinical monitoring, and brain–computer interface systems.

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