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Form factor meets function: anatomy-dependent electrode-skin coupling and signal content in consumer eyewear EEG systems

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Abstract

Objective. To evaluate the influence of head morphology on the performance of a wearable setup that incorporates the constraints of an eyewear-electroencephalography (EEG) device suitable for consumer-level applications. Specifically, the study aimed to characterize the electrode-skin impedance of two dry-electrode types mounted on eyeglass frames, assess the system's ability to capture alpha-rhythm modulation during eyes-open and eyes-closed (EOEC) states in the temporal region, and its capability to detect auditory event-related potentials (P300). **Approach.** A prototype was built by embedding four EEG electrodes, two gold-plated retractile pins (GPR) and two conductive elastomer (CoE), into a commercial eyeglass frame, with reference and bias on the nose pads. Signals were acquired using an OpenBCI Cyton board (ADS1299 analog front end, sampling at 256 Hz). Twenty young healthy adults underwent three experimental protocols, namely electrode-skin contact assessment, EOEC tasks (two cycles of 2 min each) to examine alpha-band (8–12 Hz) power changes and compute an alpha-to-broadband power ratio, and an auditory oddball paradigm (80% standard, 20% odd stimuli, 50 odd trials) to elicit and analyze P300 components. **Main results.** GPR electrodes exhibited moderately higher median impedance but slightly narrower confidence intervals compared to CoE electrodes. Head breadth significantly affected GPR impedance ($\approx 11.7\%$ decrease per mm increase), but had no significant effect on CoE impedance. Alpha-band power increased significantly during eyes-closed periods across subjects and electrode types. P300 responses (positive deflection at 300 ms) were reliably detected, with GPR electrodes yielding tighter latency distributions. **Significance.** These findings emphasize the importance of careful design considerations in wearable-EEG to account for inter-subject head anatomy variability and demonstrate that eyeglass-integrated EEG, can reliably capture both evoked and spontaneous neural responses.

1. Introduction

Wearable electroencephalography (EEG) systems are increasingly employed for real-world neurophysiological monitoring, enabling continuous brain signal acquisition outside controlled laboratory or clinical environments [1]. Such systems have potential applications in cognitive neuroscience, brain-computer interfaces, and neurorehabilitation [2–4]. Among wearable EEG devices, eyewear-integrated systems offer a particularly advantageous form factor by embedding electrodes into everyday spectacles,

enabling unobtrusive and user-friendly recording while preserving comfort and social acceptability [5].

Despite these advantages, reliable signal acquisition in constrained form factors remains challenging due to limited electrode coverage, variable electrode-skin contact, and inter-subject anatomical variability [6]. Robust detection of electrophysiological markers under these constraints is essential to validate the practical utility of wearable EEG for research and clinical applications [7]. Alpha rhythm modulation during eyes-open/eyes-closed (EOEC) protocols [8–10] and P300 event-related potentials (ERPs) [11–13]

elicited by oddball paradigms constitute widely used benchmarks for system sensitivity, signal fidelity, and temporal resolution. Moreover, both paradigms elicit robust cognitive responses that are largely subject-independent, as they rely on fundamental neurophysiological mechanisms (alpha suppression with visual engagement and attentional resource allocation to rare stimuli) rather than requiring extensive training or learned behaviors [14, 15]. Prior wearable EEG validations have largely been restricted to small cohorts or single-subject analyses, limiting generalizability and precluding systematic evaluation of anatomical influences on electrode performance [16].

In this study, we present a comprehensive assessment of a custom-built eyewear EEG frame incorporating two dry electrode types: gold-plated retractile pins (GPR) and soft conductive elastomer (CoE). The evaluation encompasses three critical dimensions: (i) electrode–skin impedance characteristics, (ii) alpha rhythm modulation during EOEC tasks, and (iii) P300 responses elicited by auditory oddball stimuli. Systematic analysis across a cohort stratified by head breadth, inter-tragion length, and head length provides novel insights into electrode design, signal reliability, and the feasibility of real-world EEG acquisition. Specifically, the objectives of this study are to:

- characterize electrode–skin impedance behavior for both GPR and CoE designs under realistic wearing conditions, assessing the stability and repeatability of the contact impedance across subjects;
- validate cognitive signal detection capability by quantifying (1) alpha rhythm modulation during EO–EC transitions; (2) auditory P300 responses elicited by oddball stimuli, highlighting temporal precision;
- investigate the influence of subject-specific anatomy, including head breadth, inter-tragion length, and head length on electrode performance and recorded EEG.

1.1. Related works

To contextualize our work within the evolution of wearable EEG technologies, we divided existing solutions into two broad categories: (1) headset-based EEG systems and (2) eyewear-integrated EEG devices. Headset or headband EEG devices have been the primary focus of commercial and research efforts aiming to simplify scalp-based recording outside the laboratory (table 1). These designs often adopt relatively standardized electrode placement geometries derived from the international 10–20 system. However, in wearable solutions, it is not always feasible to maintain these precise scalp coordinates, leading to electrode locations that may deviate substantially from standard neurophysiological landmarks,

which can affect signal fidelity, spatial specificity, and interpretability.

NeuroDotVR (NeuroFieldz Inc. USA) is a headset that integrates both virtual reality and EEG recording systems. The system is designed for neurophthalmic diagnosis and allows the presentation of visual stimuli and simultaneous EEG recording [17]. The EEG setup is based on eight custom-made hydrogel electrodes covering the O1, Oz, and O2 regions, with a reference placed on the earlobe. Given its size and purpose, this device was not designed for wearable use. The OpenBCI Ultracortex Mark IV (OpenBCI, USA) is a dry-electrode headset designed for research applications and compatible with different biosensing devices. Owing to its low cost and versatility, this setup has been used in diverse studies across BCI and emotion recognition [18]. The CGX Quick-20r (CGX Systems, USA) is a research-grade EEG headset equipped with 20 channels and dry active electrodes, with reference and bias on the earlobes, embedded electronics, and continuous impedance checking. These features, make it suitable for basic and clinical research [19]. Muse 2 (InteraXon Inc. Canada) is a consumer-grade EEG headband featuring four flat, gold-plated electrodes on hairless areas, paired with a PPG sensor for heart rate detection. It has been widely used as a portable EEG tool for ERP detection and cognitive fatigue assessment [20, 25, 26]. BrainBit (BrainBit Inc. USA) offers spring-loaded electrodes targeting temporal and occipital regions, designed for meditation, focus, and sleep analysis, and has been applied to eye movement assessment and pediatric epilepsy detection [4, 21]. Neurosteer (Neurosteer Inc. USA) uses a minimal three-electrode adhesive strip for forehead EEG acquisition, targeting neurodegenerative disease detection [3, 27]. Emotiv Insight (Emotiv, USA) and Neurosity Crown (Neurosity Inc. USA) are consumer-grade multi-channel headsets combining dry and semi-dry electrodes for emotion, focus, and performance monitoring [22, 23, 28]. The Bitbrain Diadem (Bitbrain, Spain) provides 12 scalp channels for portable research applications, often used in BCI and HRI studies [24, 29].

The shift toward EEG-enabled eyeglasses has led to the emergence of concepts, prototypes, research and commercial products for physiological monitoring [34]. Unlike headsets designed for full-scalp coverage, eyeglass-based EEG concentrates electrodes around the temples, ears, and nose bridge. While this improves wearability and aesthetics, it raises fundamental questions about whether these non-standard locations can reliably capture neural markers. Validating these placements is therefore essential for advancing wearable EEG hardware design. Furthermore, the geometric constraints of eyewear frames amplify the influence of

Table 1. Recent contributions in headset EEG systems with the description of the electrode setup (number of electrodes and their locations) and the intended purposes. The status is summarized as research platform (R), prototype (P), or commercial device (C).

Device	Electrode setup	Purpose	Status
NeuroDot VR Kit [17]	16-temporal	VEPF analysis	P
OpenBCI Mark IV [18]	8-scalp	Research	R
CGX Quick-20r [19]	23-scalp	Research	C
Muse 2 [20]	4-headband	Meditation, Focus	C
BrainBit [21]	4-headband	Sleep analysis	C
Emotiv Insight [22]	5-headset	Emotion analysis	C
NeuroSteer [3]	3-forehead	Cognitive assessment	R
Neurocity Crown [23]	8-scalp	Focus assessment	C
Bitbrain Diadem [24]	12-scalp	BCI	C

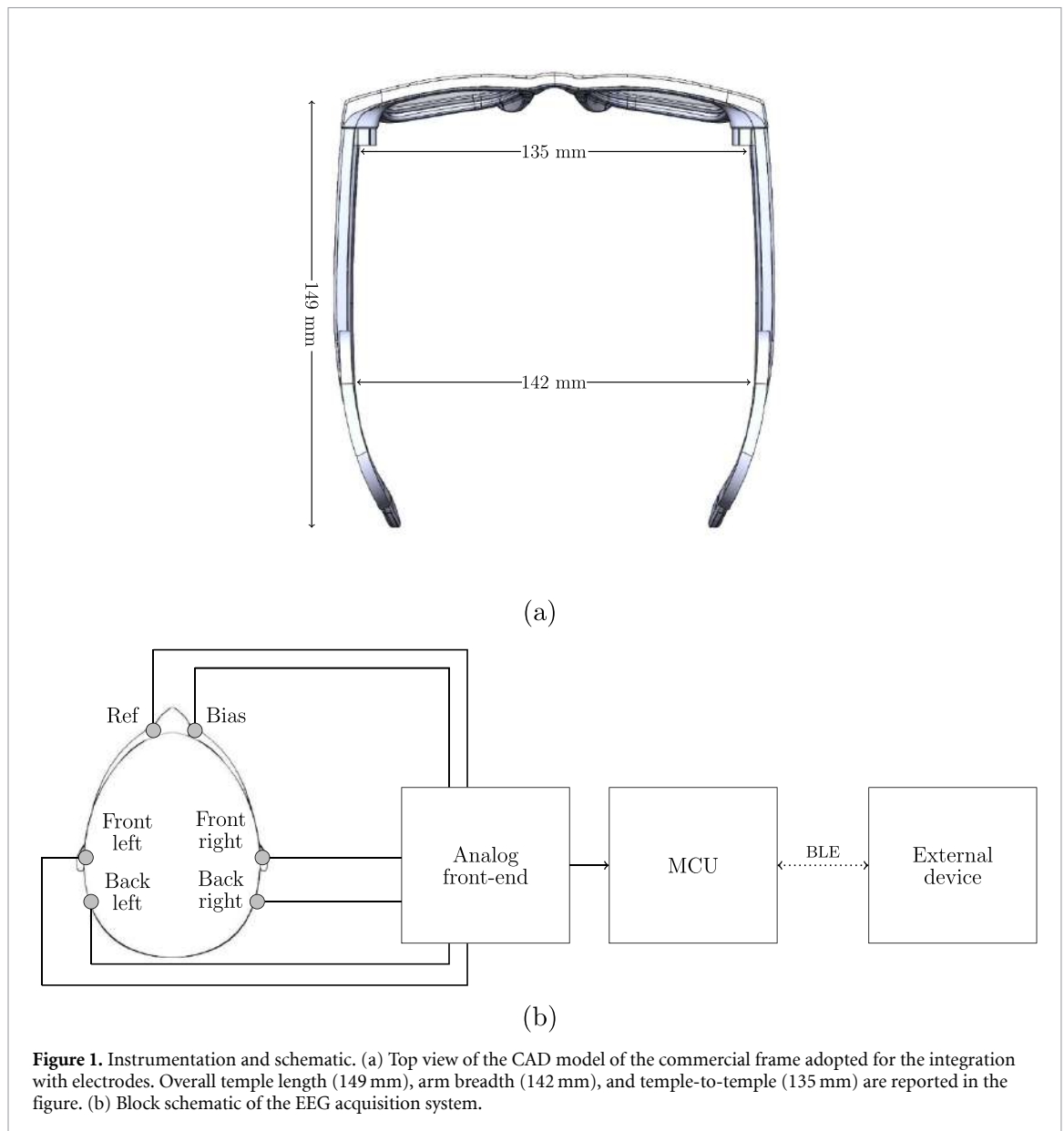
Table 2. Recent contributions in eyewear EEG systems. The status is summarized as research platform (R), prototype (P), or commercial device (C). The type of validation is related to the tests performed to validate the setup and hardware architecture: EEG inspection (EEG), alpha wave modulation in eyes-open eyes-closed (EOEC), steady-state visually evoked potentials (SSVEP), motor movement (MM); the number in parentheses is the number of subjects involved in the validation tasks. * indicates discontinued devices. ** e-Glass studies do not report validation EEG measurements performed with the proposed platform; proposed algorithms were tested on the wearable platform.

Device	Electrode number	Purpose	Validation (# subjects)	Status
AttentivU [30]	3	Cognitive performance	EEG (1)	R
AAVAA glasses	4	BCI	—	C
Smith lowdown focus	5	Focus training	—	C*
e-Glass [31]	4	Seizure detection, cognitive workload	**	R
Zero	8	Seizure detection	—	C
GAPses [32]	8	Research	EOEC (1), SSVEP (5), MM (5)	R
EEGlasses [33]	3	Research	EOEC (1), MM (1)	P
E-glasses [5]	2	Research	EOEC (10), SSVEP (10)	P

anthropometric differences (e.g. temple curvature, skull shape, hair coverage), which remain under-explored in most published studies. Table 2 summarizes the existing examples of eyewear-based EEG devices reported in the literature and available on the market, specifying the number of electrodes, intended purpose, and details of eyewear setup validation, including the number of subjects involved.

AttentivU is a research prototype of smart glasses enabling EEG and EOG measurements in an eyewear form factor, with electrodes at TP9/TP10 and on the nose pads for EOG. Its electronics are housed in the temple arms [30]. AttentivU has been applied to cognitive workload classification and wearable BCI studies [35, 36]. AAVAA glasses (AAVAA Inc. Canada) integrate four EEG channels with gesture and head movement sensors for hands-free interaction. The Smith Lowdown Focus is a now-discontinued consumer-grade eyewear solution that emphasized aesthetics and social acceptability, integrating EEG, EOG, and EMG sensors. The e-Glass is a research platform with four EEG channels (around F7, F8, T7, and T8), embedded electronics, and algorithms optimized for the detection of epileptic seizures and cognitive workload monitoring [31, 37].

Zero glasses (SK Biopharmaceuticals, South Korea) target epilepsy monitoring, embedding eight electrodes connected to temple tips for seizure detection. GAPses is a research prototype featuring pronged electrodes for improved contact in hairy regions, validated in steady-state visual evoked potential and oculomotor detection protocols [32]. EEGlasses is an early research prototype featuring three EEG channels (two electrodes on the temple tips and one above the nose bridge, with reference and bias on the nose pads). Signal recording was performed on an external biosensing board. The whole setup was tested on one subject in a single motor-action session [33]. The challenge of maintaining a stable contact with the head was also addressed in the E-glasses. Soft polymeric electrodes were mounted on a spring-loaded mechanism integrated in the eyeglasses' temples to ensure constant contact pressure on a wide range of head's dimensions [5]. Despite these innovations, none of these studies systematically correlate performance with anthropometric diversity, nor rigorously benchmark non-standard electrode placements against conventional neurophysiological markers. This motivates our focus on impedance and ERP validation at temple and over-ear sites.



2. Materials and methods

2.1. Eyewear architecture

We developed the EEG eyewear prototype incorporating four EEG sensing electrodes (two per temple) and two additional electrodes on the nose pads for signal reference and biasing in the design of a commercially available frame. This approach integrates electrodes into conventional, already available eyewear design, enabling the study of EEG signal acquisition using a real and widely adopted fixed-size consumer frame, with the ultimate goal of making neurophysiological measurements more accessible.

A view of the adopted frame is reported in figure 1(a), with reported key dimensions relevant to the contact between head and electrodes: overall temple length (distance from frame front to temple tip), arm breadth (distance between temples in correspondence with the curvature), and

temple-to-temple distance. The proposed EEG system features electrode mounting sites at the distal ends of each eyewear stem, positioned to align with the temporal regions when worn, approximately corresponding to the T5, T7, T6, and T8 locations of the international 10–20 system. These mounting sites accommodate dry brush electrodes through apertures designed for secure electrode insertion while preserving user comfort. Brush electrodes are essential for EEG applications as they provide consistent scalp-electrode contact despite variations in hair presence and head shape across users. We employed two types of brush electrodes: GPR (BrainBit Inc. USA) and CoE SoftPulse (Datwyler Inc. Switzerland) with Ag/AgCl coating. Each stem of the EEG-enabled eyewear was equipped with both electrode types (GPR and CoE). To eliminate position-based bias in performance assessment, electrodes were randomly positioned in either the front or back aperture of each

stem. The reference and bias electrodes were strategically placed on the nose pads to maintain a sufficient distance from the sensing electrodes while minimizing contamination from brain-related electrical activity. This placement provides stable reference points while remaining unobtrusive in the overall design.

The EEG-enabled eyewear prototype was designed to interface with a biosensing board containing an analog front-end, a microcontroller unit (MCU), and wireless communication capabilities. For our experimental setup (figure 1(b)), we utilized the OpenBCI Cyton, an open-source biosensing board equipped with the ADS1299 (Texas Instruments Inc. USA) analog front-end, a 24-bit low-noise ADC with integrated multiplexer, programmable gain amplifier, and right-leg drive circuit. This component was selected for its low-noise characteristics and high resolution, with the sampling frequency set at 256 Hz. The onboard PIC32MX MCU managed data transmission via bluetooth low energy protocol to an external device.

2.2. Experimental validation protocols

We designed a comprehensive three-phase experimental validation protocol to assess skin-electrode impedance, neural responses, and the effect of head dimensions. Twenty participants (age 26.3 ± 3.23 years, 8 females) were recruited for the study, each of them took part in all the protocol phases. The following anatomical dimensions of the head were measured for each participant using a small bone caliper [38]:

- Head breadth: maximum horizontal breadth of the head above the ears;
- Intertragon length: distance between tragon points on the two sides of the head;
- Head length: distance from the glabella to the opisthocranium.

This study was conducted in accordance with the Declaration of Helsinki. The study and data acquisition were approved by Politecnico di Milano Ethical Committee (Opinion 46/2023, 18 December 2023). All adult participants provided written informed consent to participate in this study.

2.2.1. Impedance characterization

Electrode-skin interface impedance was characterized using a PalmSens4 potentiostat (PalmSens BV) in a two-electrode configuration. The device generated a sine wave (100 mV_{rms} amplitude, 0 V bias) sweeping frequencies between 0.5 Hz and 10 kHz. Impedance was measured in two configurations: with a gel electrode placed on the neck, just below the ear (figure 2(a)) acting as the reference and counter; with reference and counter on the nose pad, exploiting

the EEG reference and bias dry electrodes. The working electrodes under test were positioned in the eyewear frame apertures in the temporal region in both cases. The first configuration was intended to purely perform a skin-electrode impedance contact measure. On the other hand, the second configuration was devised to closely simulate the setup of our EEG-enabled eyeglass prototype. To ensure measurement reliability, each electrode underwent three test cycles per subject, allowing us to assess the consistency of the electrode-skin interface characteristics and verify measurement reproducibility.

The fit of a fixed-size frame is strongly influenced by anthropometric factors; therefore skin-electrode contact impedance association with head morphology was evaluated using linear mixed-effects models (LMM). The models' dependent variable was $\log_{10}$ -transformed impedance at 10 Hz (measured with reference electrode on the neck). Each model included subject as a random intercept to account for repeated measurements (three repetitions per electrode type), while head breadth, intertragon length, and head length as fixed-effect regressors.

2.2.2. Alpha rhythm modulation

Another validation phase assessed the system's ability to detect characteristic EEG rhythms in the temporal area using a structured EOEC protocol (Berger's effect). Participants completed two cycles, each consisting of 2 min with eyes open followed by 2 min with eyes closed, resulting in a total protocol duration of 8 min (figure 3(a)). Participants were instructed to remain as still as possible and reduce eye movements during the experiment. This protocol was specifically devised to analyze the characteristic eyes-closed response, marked by increased alpha-band activity, in the temporal area, extending traditional measurements that typically focus on the occipital region. EEG signal was band-pass filtered between 0.5 Hz and 30 Hz, after which it was qualitatively inspected, and signal segments affected by ocular artifacts were discarded.

Moreover, the prevalence of alpha-band power in the eyes-closed phase (α_p) was used to assess the signal quality and the strength of the neural response of interest in the measured EEG. This metric was defined as:

$$\alpha_p = 10 \cdot \log_{10} \left(\frac{P_\alpha}{P_{\text{non-}\alpha}} \right)$$

where:

- P_α is the power in the [8–12] Hz band in the eyes-closed phase normalized by the power in the same frequency range in the eyes-open phase;
- $P_{\text{non-}\alpha}$ is the power in the [1–7] $\cup$ [13–30] Hz band in the eyes-closed phase normalized by the power in the same frequency range during the eyes-open phase.

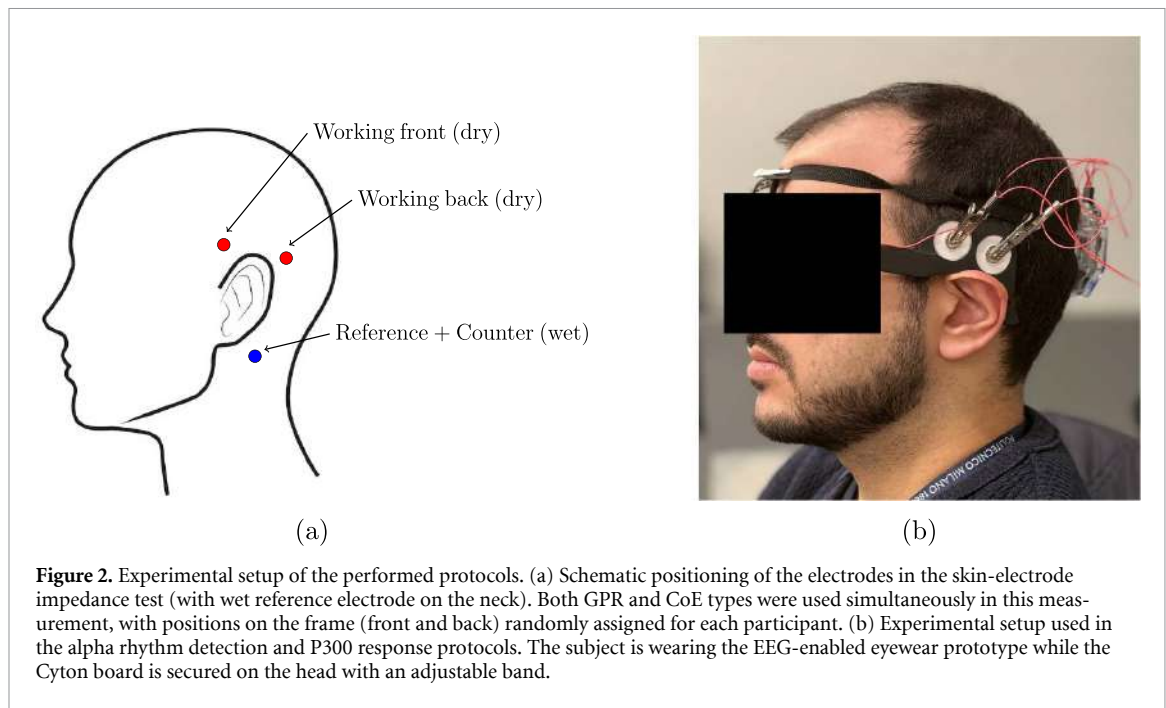


Figure 2. Experimental setup of the performed protocols. (a) Schematic positioning of the electrodes in the skin-electrode impedance test (with wet reference electrode on the neck). Both GPR and CoE types were used simultaneously in this measurement, with positions on the frame (front and back) randomly assigned for each participant. (b) Experimental setup used in the alpha rhythm detection and P300 response protocols. The subject is wearing the EEG-enabled eyewear prototype while the Cyton board is secured on the head with an adjustable band.

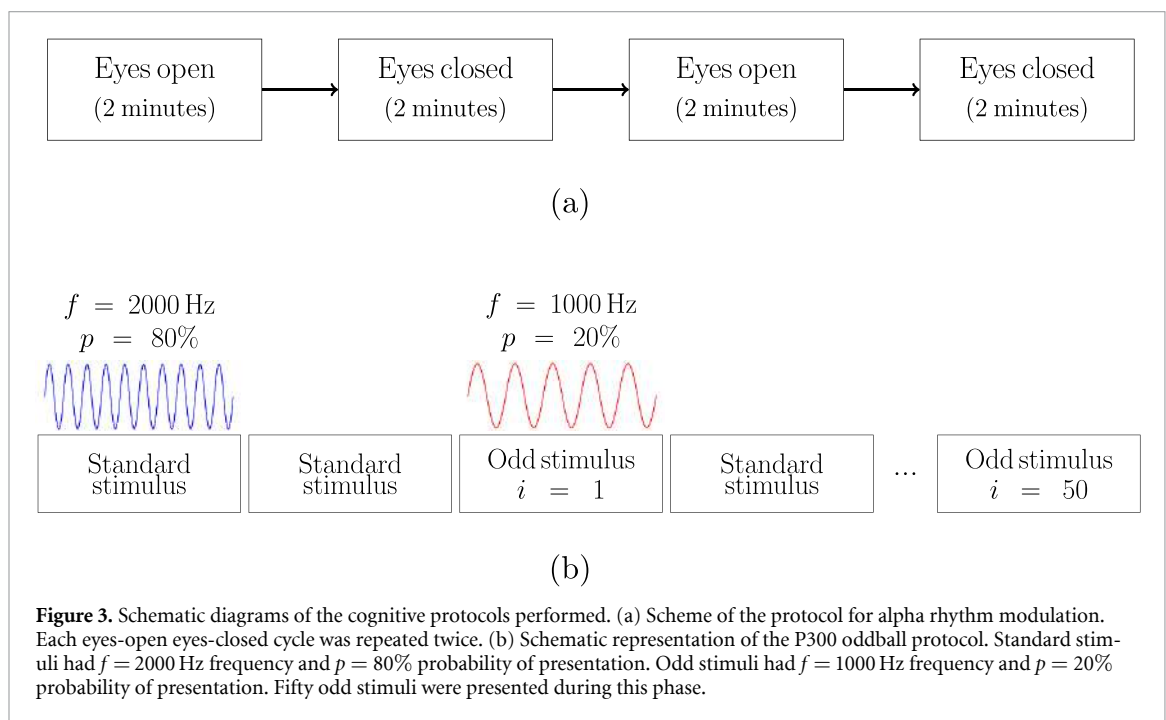


Figure 3. Schematic diagrams of the cognitive protocols performed. (a) Scheme of the protocol for alpha rhythm modulation. Each eyes-open eyes-closed cycle was repeated twice. (b) Schematic representation of the P300 oddball protocol. Standard stimuli had $f = 2000$ Hz frequency and $p = 80\%$ probability of presentation. Odd stimuli had $f = 1000$ Hz frequency and $p = 20\%$ probability of presentation. Fifty odd stimuli were presented during this phase.

The information about head dimensions was incorporated to evaluate whether these factors influence the detection of this phenomenon with the electrode types considered in this study. Detection of this response in the temporal region would validate the effectiveness of our electrode placement and signal acquisition capabilities.

2.2.3. P300 response

To evaluate the system's capability to detect standard ERPs, we implemented an auditory oddball paradigm. The protocol utilized two distinct audio stimuli delivered through ER2SE in-ear earphones

(Etymotic Research Inc. USA): a standard stimulus (2000 Hz beep lasting 100 cycles) presented with 80% probability, and an odd stimulus (1000 Hz beep lasting 50 cycles) presented with 20% probability. Each odd stimulus was presented 50 times to obtain a reliable response profile for each subject (figure 3(b)). This number was specifically chosen to facilitate grand average analysis of individual P300 responses, as a higher number of single responses contributes to an improved signal-to-noise ratio in the calculation. In this phase as well, subjects were instructed to remain as still as possible and to minimize eye movements. EEG signal was band-pass filtered between

0.5 Hz and 30 Hz, after which it was inspected, and signal epochs with ocular artifacts were discarded.

3. Results

3.1. Impedance characterization

3.1.1. Impedance characterization

The skin-electrode impedance was measured for both electrode types (GPR and CoE) in the two mounting positions (front and back) on the EEG-enabled eyewear frame using a gel electrode on the neck as reference and counter. Figure 4(a) presents the impedance values measured with this configuration across the considered frequencies, reported as median and 95% confidence interval. GPR electrodes exhibited a slightly higher median impedance than CoE electrodes, but with narrower confidence intervals for both positions. Electrodes in the back position showed greater variability in impedance values compared to those in the front position across all subjects. The skin-electrode impedance was measured for GPR and CoE in both mounting positions (front and back) with the reference on the nose pad (dry electrode integrated in the frame). The median impedance is comparable between positions and electrode types, but higher dispersions can be observed for the back position (figure 4(b)).

3.1.2. Effect of head anatomical features on skin-electrode impedance

The considered anatomical variables (head breadth, intertrigion length, and head length) describe the head morphology and are expected to be correlated to each other. The preliminary inspection of the fixed-effect regressors revealed moderate to strong correlation among variables ($r > 0.7$), and the corresponding variance inflation factor ($VIF > 2$) indicated multicollinearity among regressors. Due to the inter-correlation of the anatomical variables, each head dimension was evaluated in a separate LMM to avoid unstable estimations. The effect on GPR and CoE electrodes was analyzed separately. For each electrode type, models were fitted using three repeated measurements per subject across 20 participants, yielding a total of 60 observations. For GPR electrodes, all three head dimensions exhibited a significant (at 0.05 significance level) negative association with $\log_{10}$ impedance (table 3). The strongest effect is associated with head breadth ($\beta = -0.054$) and the weakest with head length ($\beta = -0.025$). Back-transforming the coefficients from the $\log_{10}$ -transformed to the original impedance scale, yields the following percent changes in impedance per 1 mm increase in each dimension: head breadth $\approx -11.7\%$, intertrigion length $\approx -8.6\%$, and head length $\approx -5.6\%$. The model intercepts are not interpretable at an anatomical size equal to zero. No significant effects were observed for the CoE electrodes (all p -value > 0.1).

Based on these results, the subsequent analyses focus exclusively on head breadth as the anatomical variable of interest. Impedance values are reported for the population divided into two groups according to the median head breadth value. Figure 5(a) shows the impedance values (measured with a gel reference electrode on the neck) in the tested range of frequencies for both electrode types and the two experimental groups, reported as median and 95% confidence interval. The *below median* group shows higher median impedance and larger variability than the *above median* group. GPR electrodes achieved the smallest variability, especially in the *above median* group. The analysis on the impedance measured with respect to dry electrodes on the nose pad (figure 5(b)) clearly shows lower median impedance in subjects with higher head breadth. CoE electrodes exhibit comparable variability in the two groups, whereas GPR ones show more dispersed impedance values in the *above median* group.

3.2. Alpha rhythm modulation

The modulation of alpha rhythms during alternating EOEC periods was analyzed. Figure 6 shows representative data from a single subject, presenting both time–frequency spectrograms and the derived alpha ratio for each channel. The spectrograms revealed power changes in the alpha frequency range, with visible increases during eyes-closed periods. The alpha ratio, calculated as the ratio between alpha band power, [8–12] Hz, and broadband power, [1–30] Hz, showed a clear temporal correlation with the eyes-closed states.

A comparative analysis of alpha ratio values during EOEC conditions (repeated twice), for both electrode types on both sides of the head, was conducted to evaluate consistency across subjects and electrode types (figure 7(a)). The increase of the alpha ratio can be observed for both sides of the head and with all electrode types, with alpha ratio medians in the eyes-open phase below 1.5, and above this threshold in the eyes-closed phase in all cases. To compare the distributions of the alpha ratio between EOEC conditions across electrode types and head sides, the two-sided Wilcoxon signed-rank test ($N = 40$) was applied, with Bonferroni correction for multiple comparisons. The statistical analyses proved the existence of a significant difference among the medians of the distribution in each of the considered pairs (Bonferroni corrected p -value < 0.001 for all pairs across the head sides and types of electrodes) at a significance level of 0.05. The Hodges–Lehmann median estimator of the median differences revealed a consistent decrease of the alpha ratio from eyes-open to eyes-closed condition (median differences ranging from -0.23 to -0.36) with bootstrap 95% confidence intervals entirely below zero. The rank-biserial correlation indicated a large negative effect size ($|r_{tb}| > 0.85$).

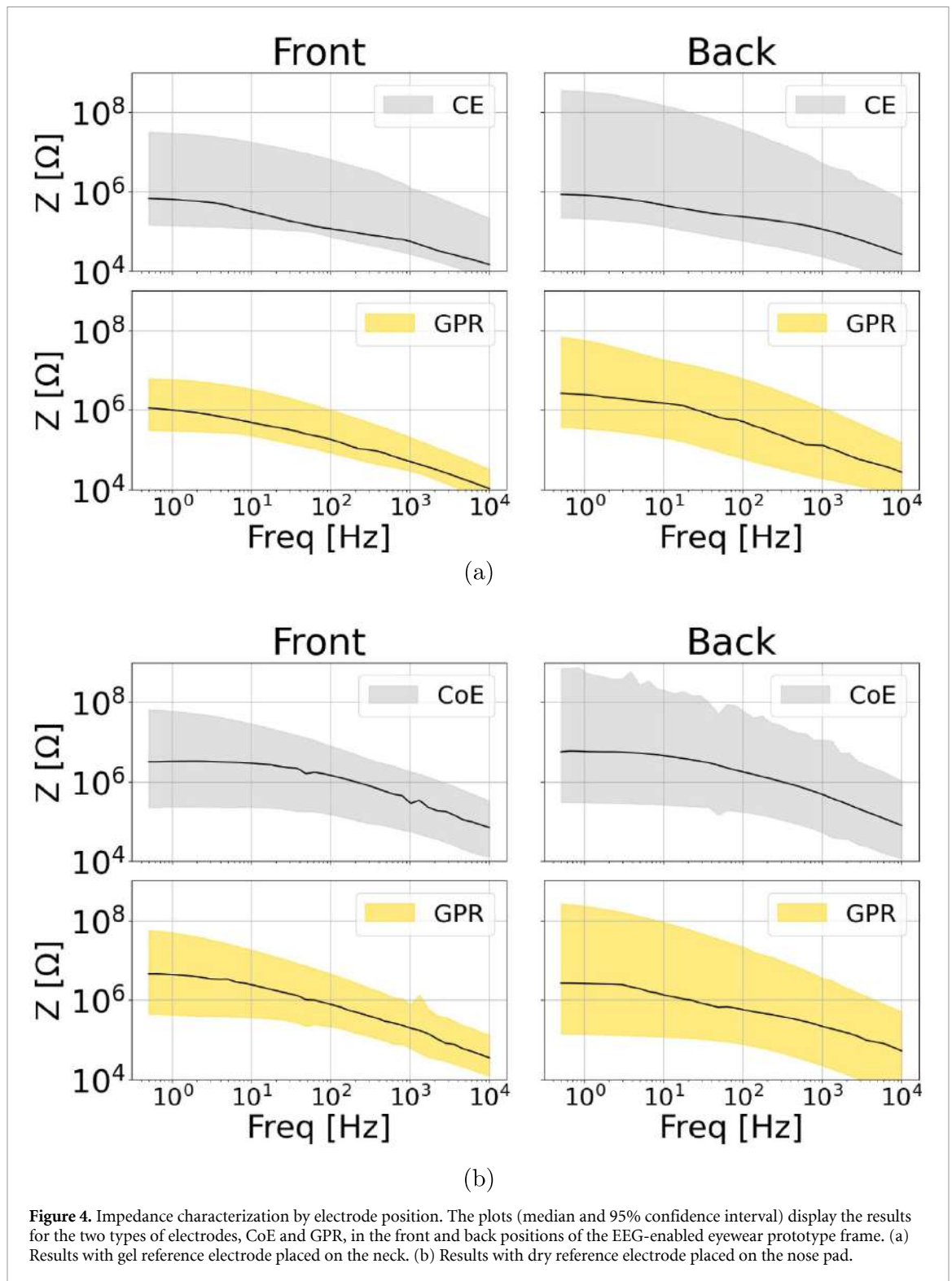
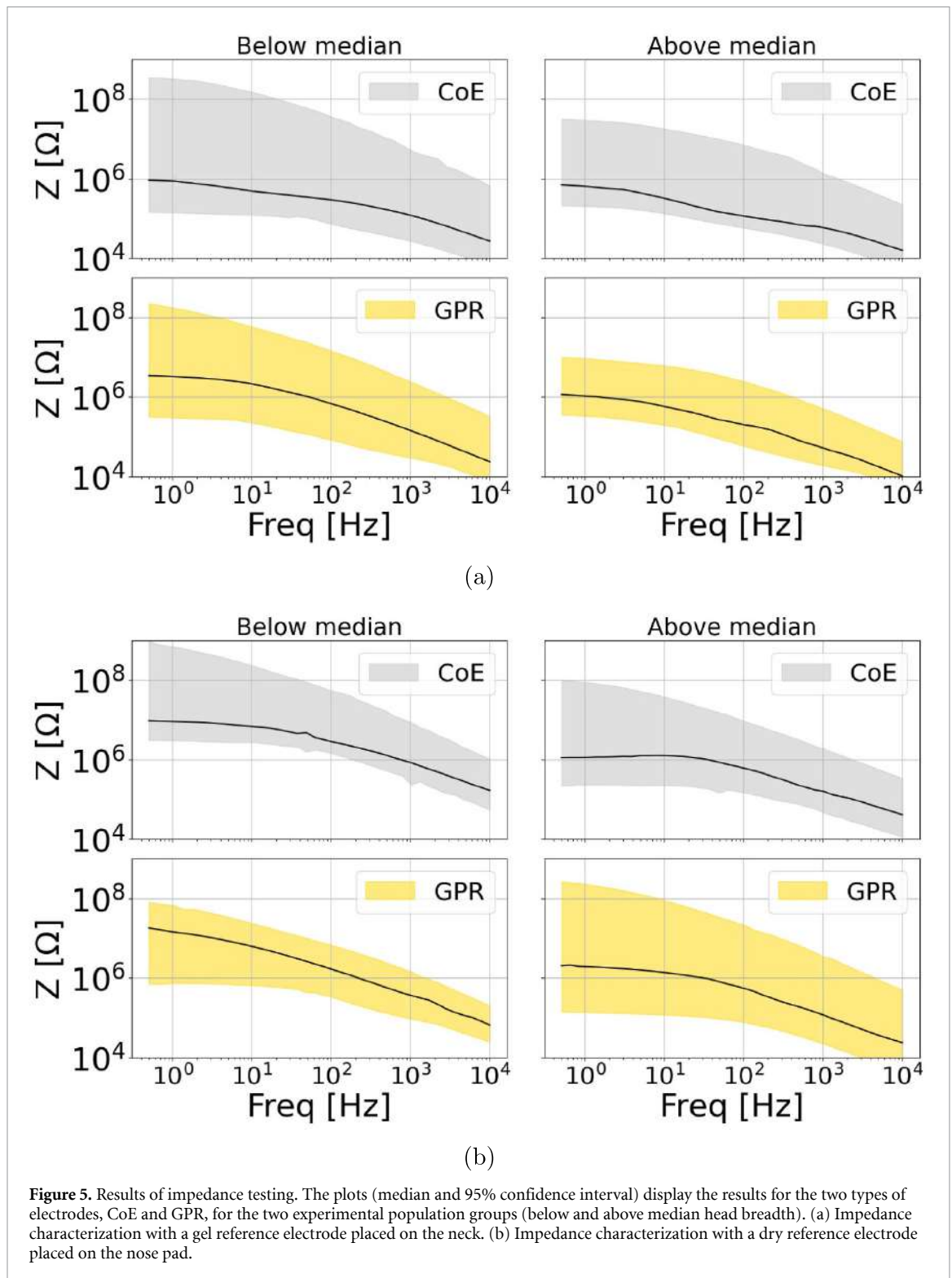


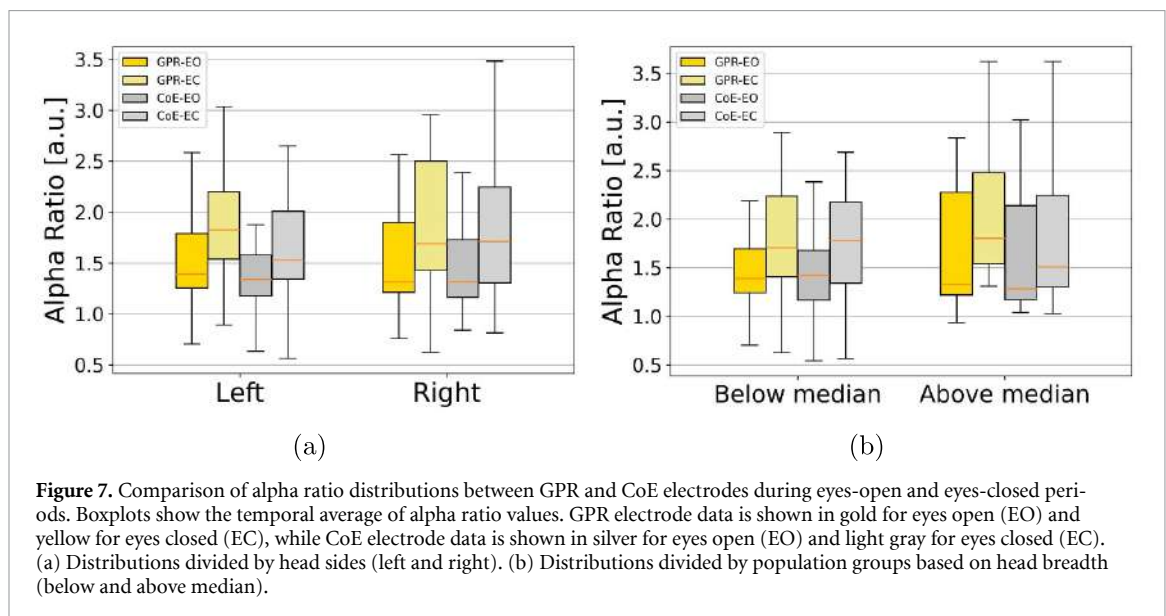
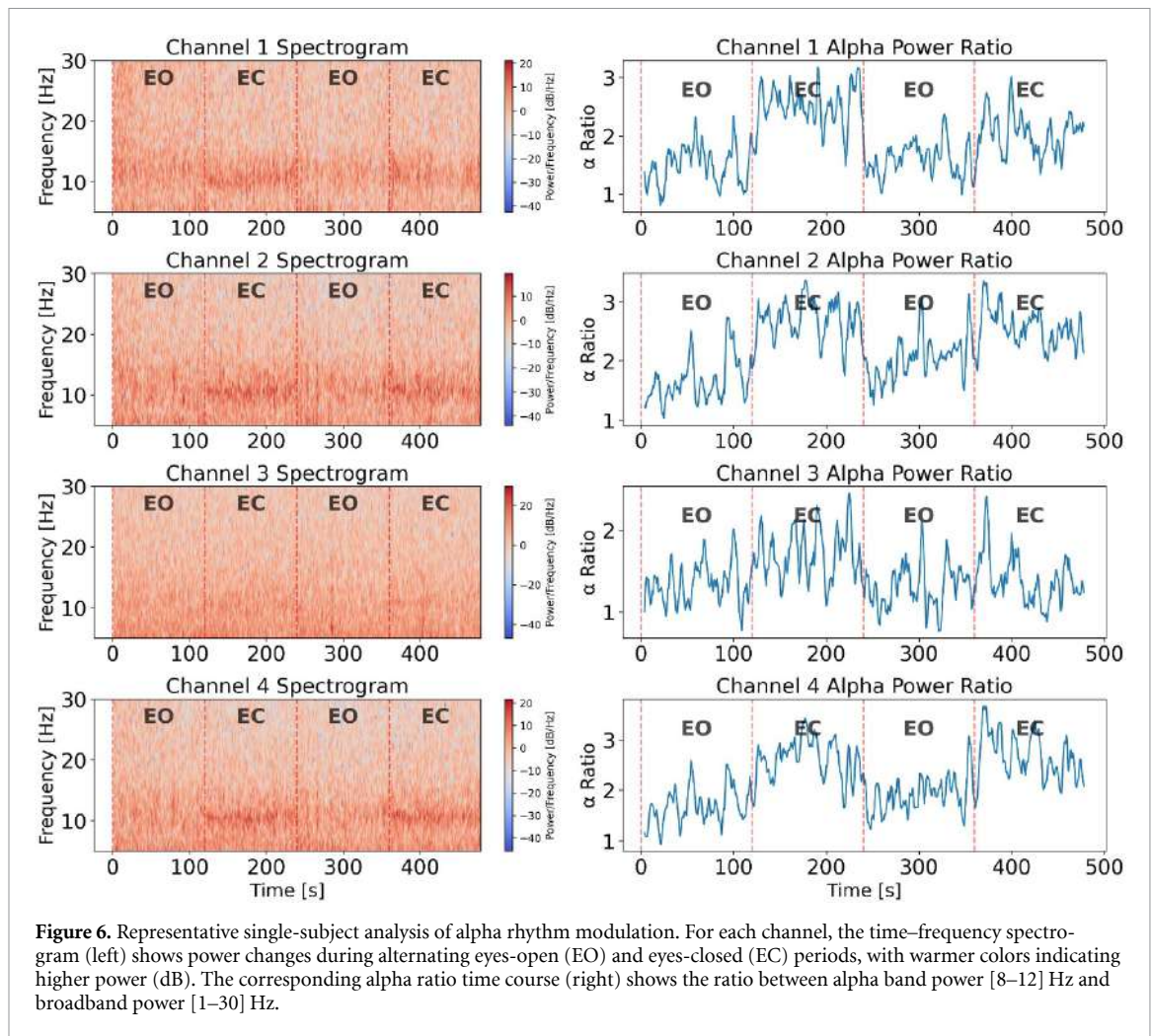
Table 3. Results for the GPR electrodes of the LMM fitted to the $\log_{10}$ -transformed impedance using subject as random effect and head dimensions as fixed-effect regressors. The table reports coefficients (β), standard errors (SE), 95 % confidence intervals (CI), and two-sided p -values.

Regressor	β	SE	95% CI	p -value
Head breadth	−0.054	0.024	−0.1, −0.008	0.023
Intertragon length	−0.039	0.018	−0.075, −0.003	0.032
Head length	−0.025	0.012	−0.048, −0.002	0.03



Alpha ratios were also analyzed with respect to head breadth, with the population divided into two groups based on the median head breadth value. The results are presented in figure 7(b), which compares the average alpha ratio in eyes-open and closed conditions across all electrode types and groups. An increase in alpha ratio from eyes-open to eyes-closed can be observed for all electrode types and across head breadth groups (alpha ratio medians

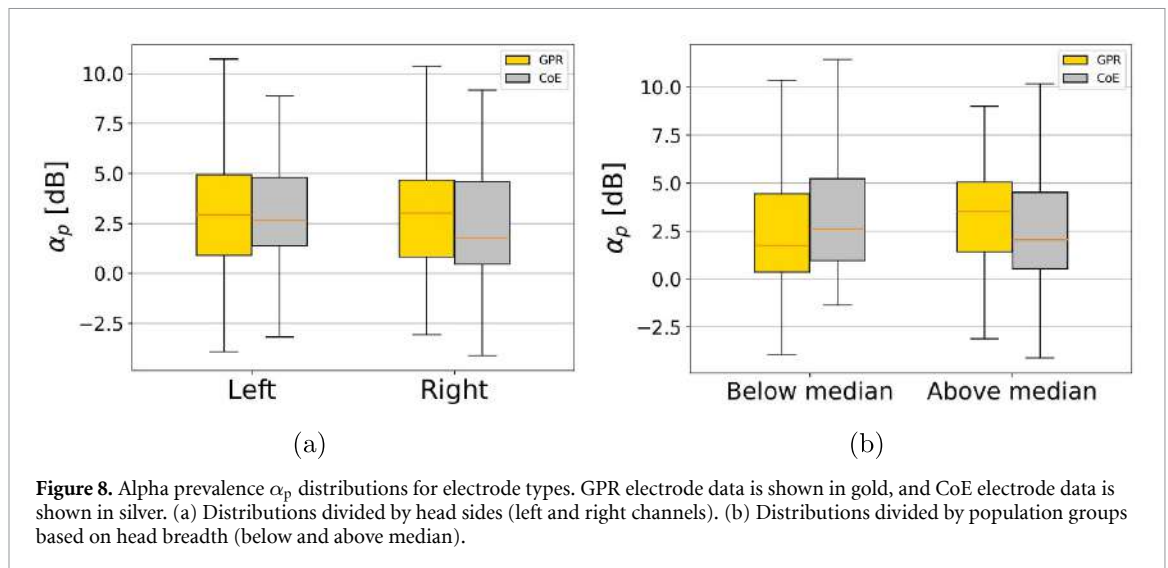
consistently below 1.5 during eyes-open in all cases). The two-sided Wilcoxon signed-rank test ($N = 40$), with Bonferroni correction for multiple comparisons, was applied on the EO-EC pairs, confirming the presence of a statistically significant difference at a significance threshold of 0.05 (Bonferroni corrected p -value < 0.001 for all EO-EC pairs across the experimental groups and electrode types). The Hodges–Lehmann median estimator of the median



differences indicated a reduction of the alpha ratio from eyes-open to eyes-closed condition (median differences ranging from -0.19 to -0.37) with bootstrap 95% confidence intervals consistently below zero. The rank-biserial further confirmed a large negative effect size ($|r_{tb}| > 0.86$).

3.2.1. Alpha prevalence estimation

The alpha prevalence provides additional insight into the signal quality during the EOEC protocol. The distribution of α_p for both electrode types and head sides shows that the median, along with the first and third quartiles, are consistently greater than zero (left GPR:



2.92 dB [0.90, 4.92]; left CoE: 2.66 dB [1.38, 4.80]; right GPR: 3.0 dB [0.83, 4.67]; right CoE: 1.75 dB [0.45, 4.57]), indicating the prevalence of the signal of interest (i.e. alpha rhythm) during the eyes-closed phase, with a very similar behavior between the right and left sides of the head (figure 8(a)). To assess whether significant differences exist among the α_p measured with each electrode type and head side, the Kruskal–Wallis test revealed no statistically significant differences at a 0.05 significance level (p -value = 0.77). The estimated effect size confirmed negligible effects due to side and electrode types ($\epsilon^2 = 0$). The α_p was also analyzed considering the groups based on head breadth (figure 8(b)), showing an overall good performance of both electrode types and in the two head groups below and above head breadth: below median GPR 1.76 dB [0.36, 4.44]; below median CoE: 2.58 dB [0.95, 5.23]; above median GPR: 3.51 dB [1.40, 5.03]; above median CoE: 2.03 dB [0.52, 4.51]. The Kruskal–Wallis test indicated absence of statistically significant differences at a 0.05 significance level (p -value = 0.24) among groups and electrode types. The estimated effect size confirmed negligible ($\epsilon^2 = 0.008$) effect on the α_p .

3.3. P300 response

The ERPs elicited by both odd and standard auditory stimuli were recorded across all four electrode positions. Figure 9 presents the grand average waveforms recorded for one subject for both stimulus types. A positive deflection was observed at approximately 300 ms following the odd stimulus presentation, while the standard stimulus elicited a minimal response. This pattern was consistent across all electrode positions. The ratios between amplitudes of standard and odd peaks in the grand average were computed to verify the presence of the expected response (table 4(a)). The median P300

latency was consistently around 300 ms for both electrode types and positions (table 4(b)). GPR electrodes demonstrated more concentrated latency distributions, while CoE electrodes exhibited wider interquartile ranges across all positions.

4. Discussion

The results of this study provide insights into the influence of anthropometric factors on eyewear-based EEG recording employing two types of dry electrodes mounted on a positioning frame. The impedance characterization confirmed that GPR electrodes (cfr. figure 4(a)), despite showing higher median impedance values than CoE electrodes, exhibited slightly narrower confidence intervals, suggesting superior signal consistency. This aligns with the findings in [39], who noted that spring-loaded dry electrodes offer more reliable contact across varying skin and hair conditions than soft polymer electrodes. The results of the effect of head dimensions estimated with LMM show a different behavior for the two types of electrodes. For GPR electrodes, larger head dimensions are associated with lower impedance at 10 Hz. The head breadth has the largest effect, with a reduction of $\approx 11.7\%$ per 1 mm increase of that dimension (cfr. figure 5(a)). The other considered dimensions, intertrigion length and head length, exhibit lower but significant influence (reduction of $\approx 8.6\%$ and $\approx 5.6\%$ respectively). The comparable, although different magnitude of the head dimensions effect should be interpreted as the expression of an underlying common geometric factor (head shape). In other words, participants with larger or broader heads tended to show lower skin-electrode impedance at 10 Hz, regardless of the specific anatomical measure used to represent head size. On the other hand, the absence of significant associations between anatomical regressors and impedance at 10 Hz was observed for the CoE electrodes.

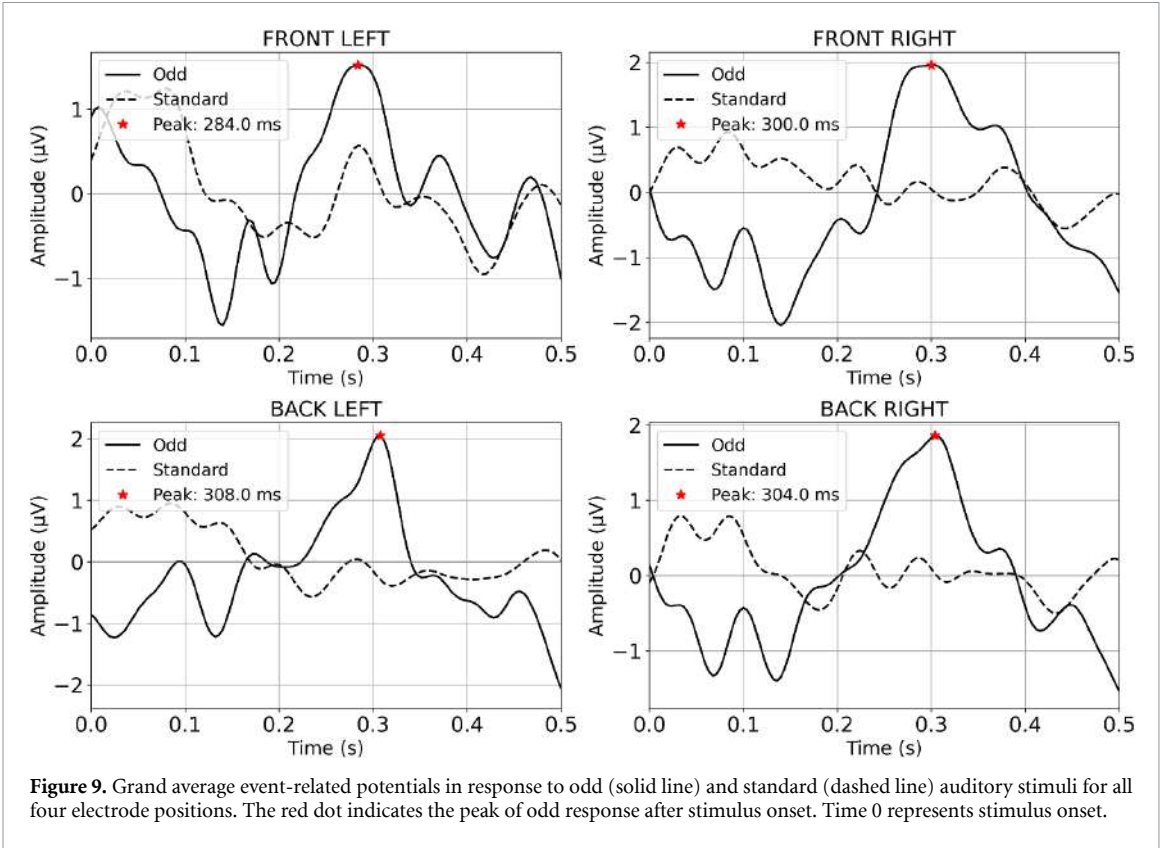


Figure 9. Grand average event-related potentials in response to odd (solid line) and standard (dashed line) auditory stimuli for all four electrode positions. The red dot indicates the peak of odd response after stimulus onset. Time 0 represents stimulus onset.

Table 4. P300 oddball protocol results presented as median and first and third quartiles, on right and left side of the head, and for the two types of electrodes (GPR and CoE). (a) P300 standard and odd peak amplitude ratios. (b) P300 peaks latencies.			
Amplitude ratios (a.u.)		Latencies (ms)	
Left	Right	Left	Right
GPR	1.68 [1.41; 2.57]	280 [269; 304]	284 [236; 304]
CoE	2.13 [1.40; 2.78]	284 [226; 358]	280 [220; 346]

This lack of dependence suggests electrode-design-dependent sensitivity to head dimensions. Further analyses on the impedance measurements obtained with the reference placed on the nose pad show the challenges posed by subject-specific characteristics (i.e. head size) in wearable-EEG (cfr. figure 5(b)). Head morphology has a stronger influence on this configuration, as the reference electrode is also subject to sub-optimal contact conditions. Nevertheless, this measure effectively highlights the practical difficulties encountered during real-life device use. These findings emphasize that a critical design consideration for eyewear-based EEG systems is ensuring electrodes can establish large contact areas while accommodating inter-subject variability without compromising user comfort [40]. This feature is especially relevant when compared to semi-dry electrodes like those in Emotiv Insight [22], which, while easy to wear, can degrade in signal quality with extended

use or poor contact over hairy regions. The importance of an EEG setup that could accommodate the users was highlighted by Craik *et al* [41] in their design of an adjustable EEG helmet. However, the possible adjustment on eyewear was limited by the form-factor itself and social acceptability considerations. The alpha rhythms observed during the EOEC protocol (section 3.2) further validated the capability of the EEG-enabled eyewear system to detect characteristic EEG patterns. Analysis of the measured alpha ratio revealed a distinct and significant increase in power within the 8–12 Hz band during the eyes closed phase, consistently observed across all electrode channels and types and confirmed by analysis on effect size. The modulation in alpha ratio confirmed that electrodes placed over the temporal region, regardless of type, were able to capture alpha activity, a phenomenon traditionally measured in the occipital region (cfr. figure 6). Evaluation of alpha ratio across

groups stratified by head breadth demonstrated that both electrode types consistently detected alpha-band modulation within each subgroup. This indicated that the EEG-eyewear maintained stable performance across users with varying anatomical characteristics. These findings were further supported by the analysis of alpha prevalence during the eyes-closed condition (section 3.2.1), which showed robust signal quality for both electrode types across all channels, without significant differences. Concerning literature comparison, alpha rhythm modulation remains a standard benchmark for validating EEG acquisition systems. The ability of dry-electrode EEG setups to record alpha rhythm modulation was confirmed in previous studies. Marini *et al* [19] demonstrated the efficacy of such systems in detecting the characteristic alpha-band peak during the eyes-closed phase of the protocol. Radüntz [42] focused on wearable EEG devices, showing that several wearable systems showed a significant increase in parietal alpha-band power during an EOEC task compared with traditional wet-electrode setups. Also, the comparison by Kleeva *et al* [43] demonstrated the ability of EEG wearables to replicate the detection of alpha rhythm modulation of a gel EEG system. Similar validation approaches were applied in eyewear-EEG studies. In [32], the authors evaluated their GAPses system using an EOEC task on a single subject and reported an increase in alpha-band power during the eyes-closed phase. Conversely, the present study extended the validation to a substantially larger cohort and systematically evaluated performance across head dimensions, reinforcing the importance of careful design in wearable-EEG devices equipped with dry electrodes and with limited adaptability to different head shapes.

The successful detection of P300 responses across all electrode types confirmed the EEG-enabled eyewear system's ability to capture cognitive ERPs. The observed positive deflection at approximately 300 ms post-stimulus aligned with established characteristics of the P300 component, typically occurring within the 250–500 ms window following infrequent or unexpected stimuli. While median latencies were similar across electrode types, notable differences emerged in signal quality. GPR electrodes exhibited more tightly clustered latency distributions, indicating superior temporal precision and more stable signal acquisition. In contrast, CoE electrodes showed broader interquartile ranges, reflecting increased variability in peak detection, likely attributable to differences in skin-electrode contact stability and material-specific electrical properties. These findings compare favorably with results reported for other wearable EEG systems. Headset-based devices such as the Muse 2 and Emotiv Insight have demonstrated P300 detection capabilities, but often rely on

forehead-mounted [20] or semi-dry [16] electrodes that offer limited spatial coverage and are sensitive to motion artifacts. In particular, Muse 2 has been validated for cognitive ERP studies in a visual oddball paradigm but with a constrained electrode layout and reduced signal robustness over longer periods. Similarly, the GAPses [32] eyewear prototypes have shown the ability to detect steady-state visually evoked potential responses, yet their validation has often been limited to a small number of subjects or lacked comparative assessments between electrode types. In contrast, the present study systematically evaluates P300 performance across a larger cohort, two electrode types, and four electrode sites, providing a more comprehensive assessment of signal quality and repeatability. The consistent detection of P300 responses across all channels and subjects underscores the robustness of eyewear-integrated systems.

Collectively, our findings demonstrated through the custom-built prototype the feasibility and anatomically-related challenges of capturing rhythms and audio ERPs through electrodes integrated into an eyewear form factor. The consistent performance across multiple subjects with different head characteristics and experimental paradigms validates the feasibility of this approach for practical applications. GPR electrodes performed better in terms of P300 peaks latency variability, but showed dependence of skin-electrode impedance on head dimensions. However, the expected neural responses were reliably detected with both electrode types and across subjects with different prototype frame fittings. These analyses provide novel insights into the challenges associated with recording EEG signals with everyday wearable devices.

The demonstrated ability to record meaningful neural activity using a reduced set of dry electrodes integrated into an eyeglass frame supports the feasibility of conducting EEG recordings outside clinical environments. This approach highlights the potential for embedding the necessary instrumentation into everyday eyewear, enabling neurophysiological assessment outside the clinical environment.

5. Conclusions

In this study, we explored the feasibility of recording meaningful EEG signals using dry electrodes integrated into an eyewear form factor, with specific focus on the influence of anatomical characteristics on the performance and reliability of wearable EEG systems. Our evaluation focused on three critical aspects: electrode impedance characterization, assessment of cognitive processes traditionally measured in other scalp regions, specifically alpha rhythm modulation, and detection of auditory cognitive processes via P300

responses. The influence of anthropometric factors was evaluated with respect to three head dimensions: head breadth, intertragon length, and head length.

The results on impedance analyses showed lower variability in the impedance values for GPR electrodes compared with CoE ones. However, the analysis conducted on anthropometric factors revealed a dependence of GPR electrode impedance on head dimensions, which was not observed with the CoE type.

The findings on alpha rhythm modulation validate the feasibility of recording cognitive processes typically measured in occipital regions using electrodes placed in the temporal region. The detection of the expected alpha modulation was possible across the two types of electrodes and despite the dependence of GPR electrodes impedance on the head dimensions. Furthermore, the system successfully detected P300 responses, confirming the capability to capture ERPs in an eyewear-integrated form factor.

These findings offer valuable insights for future studies aimed at designing eyewear-integrated EEG systems that account for anatomical characteristics, emphasizing the importance of accommodating inter-subject variability in the mechanical and ergonomic design of wearable EEG devices. In addition, they suggest that eyewear-based EEG systems have the potential to bridge the gap between laboratory-based neurophysiological monitoring and real-world applications. Integrating EEG sensors into everyday wearables enables a practical and comfortable method for continuous brain monitoring, thereby expanding possibilities for cognitive research, brain-computer interfaces, and clinical applications.

Future work will aim to expand the system's validation to a broader population, to gain deeper insight into design-related factors that may enhance signal quality and reliability. Direct measurements of electrode contact pressure should be performed to strengthen the understanding of the influence of anatomic factors on contact impedance and signal reliability. Further studies would also benefit from the adoption of a frame with adjustable hinges that allow control of the contact pressure between the scalp and electrodes, which would help ensure more consistent signal quality during acquisitions. As a further step, the inclusion of artifact correction algorithms, such as artifact subspace reconstruction [44], ensemble empirical mode decomposition [45], and deep-learning based approaches [46], into the analysis of eyewear-EEG signals would increase the robustness of the experimental pipeline. Moreover, testing in real-world environments will be crucial to confirm the findings of this study, gather additional evidence to inform design improvements, and assess long-term usability and applicability of an eyewear-EEG system to neuroscientific studies. Finally, further efforts will focus on the optimization of electrode design, integration of recording and signal processing capabilities, and motion artifact mitigation.

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Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

NA and DT are employees of EssilorLuxottica. MR is currently employed by EssilorLuxottica; however, this employment, including the selection process, began after the submission of the manuscript. ACP, AF, PC, and LM declare no conflict of interest. The authors affirm that the study design and the results analysis, interpretation, and reporting were not influenced by the commercial interests or technological development priorities of EssilorLuxottica.

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