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Comparative Analysis of Ear Electroencephalography (Ear-EEG) and Scalp Electroencephalography (Scalp-EEG) in Wearable Brain-computer Interfaces

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Abstract

This paper compares and analyzes ear-based electroencephalography (Ear-EEG) and scalp-based electroencephalography (Scalp-EEG) in wearable brain-computer interfaces (BCIs) to examine how signal fidelity, robustness, and usability are balanced. The study evaluates signal quality (event-related potentials ERP, signal-to-noise ratio SNR), resistance to motion artifacts, comfort, wearability, and practical applicability. The results indicate that, despite moderate signal attenuation (amplitude loss of 21% to 44% compared to optimized Scalp-EEG) and limited spatial coverage (1–6 channels), Ear-EEG still achieves clinically relevant sensitivity for key auditory ERP components (Hedges' *g* = 0.25–0.77) and alpha-band oscillations. Ear-EEG has inherent resistance to ocular artifacts but is highly sensitive to interference from jaw/head movements. In terms of usability metrics, Ear-EEG significantly outperforms Scalp-EEG: the dry electrode design supports over 40 hours of continuous wear with minimal discomfort (only approximately 15% of users reported noticeable foreign body sensation), can be self-installed within 5 minutes, and has approximately 45% higher social acceptability. However, Scalp-EEG still holds advantages in whole-brain coverage, high-fidelity tasks (such as N400 semantic decoding), and motion robustness during walking (no artifacts at 3.0 km/h). Additionally, this paper demonstrates the feasibility of Ear-EEG for mobile, long-term monitoring applications (such as sleep tracking and epilepsy detection), while also clarifying the unique application scenarios where Scalp-EEG remains irreplaceable.

Keywords

Ear-EEG; Scalp-EEG; Brain–Computer Interface (BCI); Neural signal monitoring; Wearable neurotechnology.

1. Introduction

Electroencephalography (EEG) has been widely used to investigate brain activity due to its non-invasive nature and high temporal resolution. Conventional scalp-EEG, however, requires conductive gel, extensive preparation time, and may cause discomfort during long-term monitoring. To overcome these limitations, ear-EEG has emerged as a promising alternative by placing electrodes around the ear in a discreet and user-friendly manner. Recent studies have demonstrated its potential in sleep monitoring, auditory research, and mobile brain–computer interface (BCI) applications. Nevertheless, systematic comparisons between ear-EEG and scalp-EEG remain limited, especially regarding signal quality, usability, and practical deployment in real-world scenarios. This study aims to conduct a comparative analysis of ear-EEG and scalp-EEG, providing insights into their respective strengths, limitations, and potential for integration in future neurotechnology applications.

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2. Signal Quality Comparison

In one of the studies, researchers compared EAR-EEG and CAP-EEG together to compare their effects in recording auditory ERP (event-related potential).

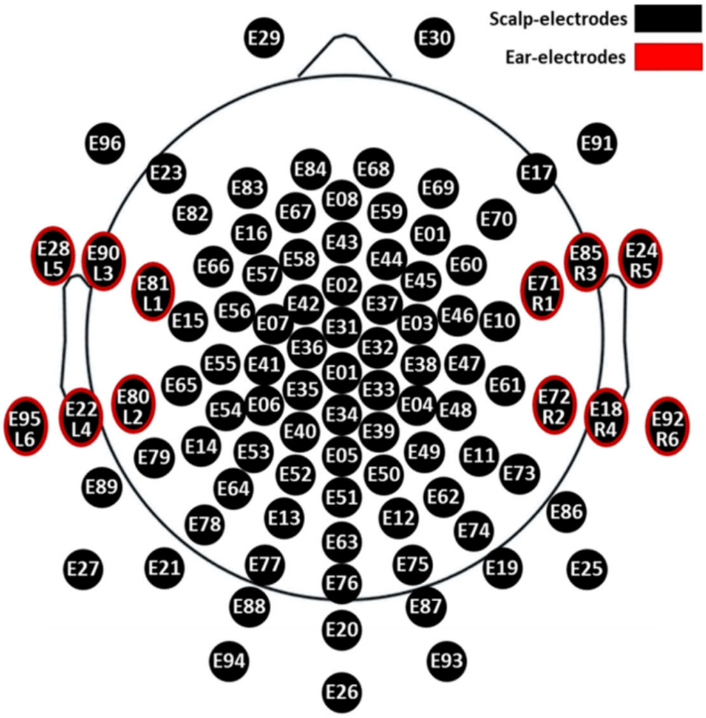

Figure 1. Channel layout of the 96 channel EEG cap. E29 and E30 are placed below the eyes. [2]

Researchers measured in detail how much signal several typical ERP components lost.

Table 1. The table shows per task in the study the signal loss from the scalp (ind.)-configuration to the other four configurations in percent.

ERP Component	Scalp (sta.)	Ear (Bilateral)	Ear (Unilateral Right)	Ear (Unilateral Left)
N100	56.97%	44.24%	49.53%	48.47%
N100 (att.)	45.33%	22.28%	28.95%	37.05%
MMN	54.63%	33.05%	41.87%	45.78%
P300	29.60%	41.81%	48.22%	44.84%
N400	50.27%	21.20%	29.78%	32.11%

Despite the loss, the effect value of ear EEG (Hedges 'g) remained between 0.25 and 0.77, namely N100: 0.77, N100(att.): 0.66, MMN: 0.25, P300: 0.58, and N400: 0.65, which indicates that Ear-EEG has achieved moderate to high effect values for key auditory ERP components, and all auditory ERP could be significantly recorded by Ear-EEG ($p<0.001$).

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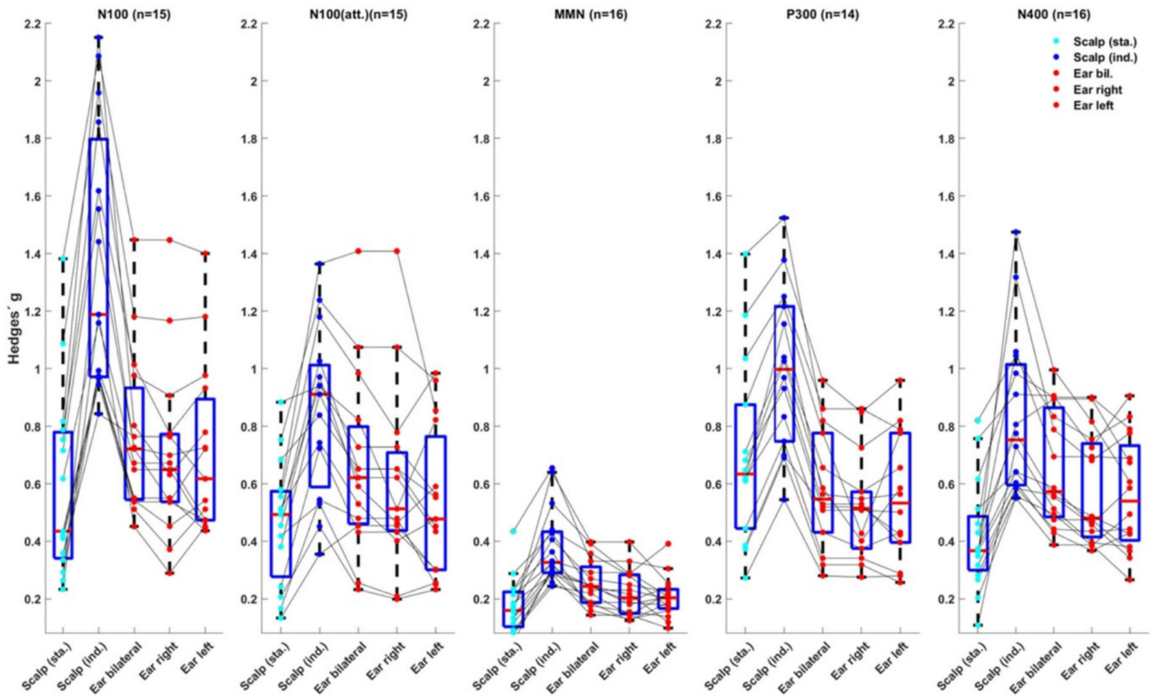

Figure 2. Boxplots of individual effect sizes over tasks and over EEG-configurations[2]

In the experiment, the shapes and occurrence times of ERP recorded by ear-EEG and Cap-EEG were highly consistent. Only the amplitude of EAR-EEG was smaller because the electrode distance on the ear was closer than that of scalp EEG.

However, among different components, the gap of P300 was the greatest: the effect value of Ear-EEG (g = 0.58) was significantly much smaller than that of Cap-EEG (g = 1.00); N400 performed the best in Ear-EEG, with only a 21% loss.

In addition, the individual differences of Ear-EEG (fluctuations in the effect value of a certain subject) are the same as the trend of Cap-EEG (Figure 2), indicating that Ear-EEG has good repeatability.

Compared with Cap-EEG, the Hedges 'g of Ear-EEG decreased by 21% to 44%, and specific components (especially P300) were lost. However, Ear-EEG still maintained medium-high sensitivity in all key auditory ERP components (g = 0.25 to 0.77). And it has good form and time fidelity. In capturing auditory ERP, Ear-EEG can serve as a simple alternative to Cap-EEG.

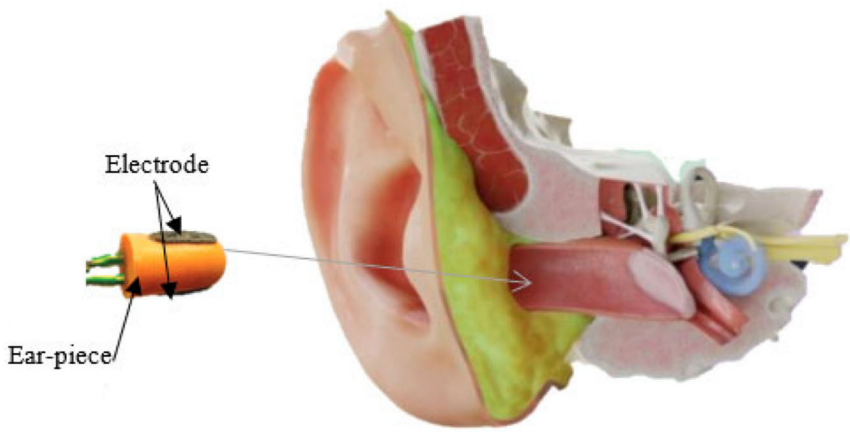

Figure 3. Comparative spectral analysis of ear-EEG and scalp-EEG signals across frequency bands

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Traditional high-density scalp EEG typically employs 8 to 256 electrodes arranged in a 10 to 20 system, while in-ear EEG systems, due to anatomical space limitations, can only use 2 to 6 electrodes placed in the external auditory canal or around the ear. The extremely small number of electrodes leads to a decline in signal quality: scalp EEG can achieve a signal-to-noise ratio (SNR) of approximately 10-20 dB and a peak amplitude of 10-100 μV under the same auditory task, while in-ear EEG can only record an SNR of 5-10 dB and an amplitude of 1-10 μV [1].

These limitations lead to a decline in spatial resolution and make it more susceptible to interference from electromyography and motion artifacts in real environments. Nevertheless, the 5-10 dB SNR of in-ear EEG is still sufficient to extract key ERP components (such as N100, P300, N400), and its effect value (Hedges' g = 0.25-0.77) indicates that it can still meet the reliable requirements for mobile neurophysiological monitoring.

3. SNR Comparison

one of the stuties shows that when facing neurosources close to the ear, such as the auditory cortex, the signal-to-noise ratio (SNR) of EAR-EEG is the same as that of nearby Cap-EEG.[3]

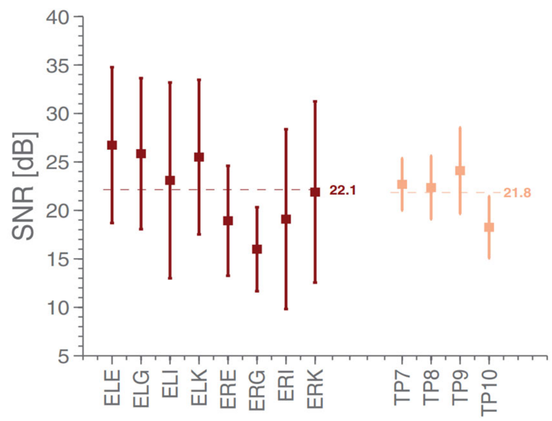

Figure 4. The mean and standard deviations of SNR estimates in the ASSR paradigm for various EEG electrodes

In the 40 Hz auditory steady-state response (ASSR) experiment, since both electrodes were placed very close to the same neural signal source, the physical characteristic of rapid attenuation of electrical signals with distance did not pose an additional disadvantage to the ear EEG.

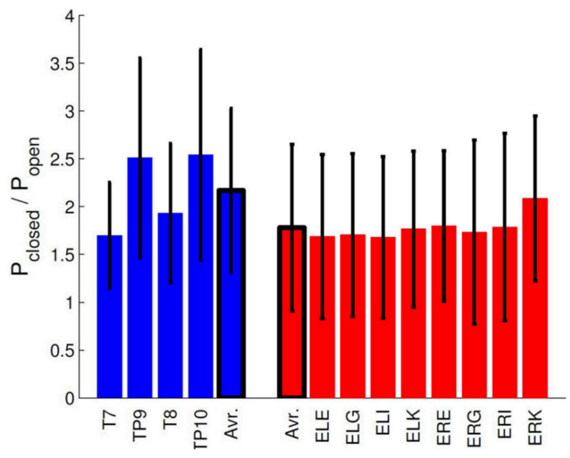

Figure 5. Comparison of α-attenuation between scalp-EEG and ear-EEG electrodes averaged across all subjects

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Figur 5 Comparison of α-attenuation in scalp and ear-EEG electrodes, averaged over all subjects

Furthermore, research indicates that ear EEG can reliably record alpha band oscillations, showing significant power differences between closed eyes (high alpha activity) and open eyes (low alpha activity). This clearly shows that it is highly suitable for frequency-domain analysis-based applications, such as sleep monitoring. However, the same study also found that since MMN mainly originates in the frontal lobe region far from the ear, ear EEG cannot effectively detect mismatch negative waves (MMN). This discovery indicates that when the signal source is at a considerable distance, the SNR will significantly decrease due to potential attenuation and the configuration of the reference electrode at a short distance. In conclusion, when ear EEG captures local auditory signals and oscillatory activities, the SNR can be comparable to that of scalp EEG, but the performance declines when targeting distant neurosources.

4. Motion Artifacts and Robustness

Under different movement states of the human body, both scalp EEG and ear EEG are affected by motion artifacts, and their robustness also varies.

A study investigated the effects of head movement on active scalp EEG when participants walked on a treadmill at speeds of 1.5–4.5 km/h. In the study, at speeds of 1.5 km/h and 3.0 km/h, the EEG spectrum retained only the typical 1/f characteristics, and researchers observed almost no harmonics generated by acceleration. Only at 4.5 km/h did individual peripheral channels (e.g., T8) exhibit mechanical coupling artifacts. Additionally, the Artifact Subspace Reconstruction (ASR) method effectively removed residual low-frequency artifacts at 4.5 km/h [5]

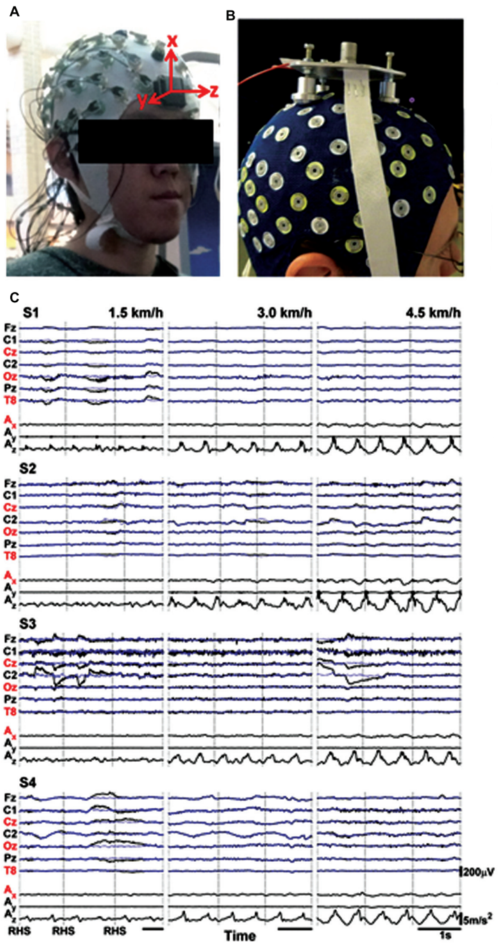

Figure 6. Experimental setup and representative raw EEG and accelerometer signals across gait cycles

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Figure 6 Experimental procedure and raw signals (A) Photos of subject and experimental setup showing active EEG cap and triaxial MARG inertial sensor mounted on the forehead (left) and of (B) subject and experimental setup from similar protocol in Castermans et al. (2014), reproduced here with permissions from the author and publisher. (C) Sample raw EEG and Accelerometer data for three gait cycles for all four subjects and all three speeds. The x-, y-, and z-axes for the accelerometer represent the vertical, mediolateral, and anterior–posterior directions respectively. Traces with red labels indicate channels chosen for further analyses. Blue traces are EEG channels after processing with ASR. Vertical black lines indicate onset of Right Heel Strikes (RHS). [5]

In conclusion, active scalp EEG demonstrates extremely high robustness against motion artifacts at everyday walking speeds, and when combined with algorithms like ASR, it can nearly restore the signal to resting-state levels.

In the second study[4], Researchers compared the impact of ear-EEG and scalp EEG on signal-to-noise ratio degradation (SNRD) of 40 Hz steady-state auditory evoked potentials (ASSR) under nine physiological artifact conditions. The study found: Under artifact conditions involving jaw movement (e.g., chewing, clenching teeth), ear EEG exhibited the highest SNRD values in the γ band, with artifacts significantly higher than scalp EEG; under blinking conditions, artifacts primarily affected the δ and θ bands of scalp EEG, while ear EEG remained largely unaffected, indicating its inherent resistance to ocular artifacts; under head movement conditions, ear EEG exhibited significant artifacts across the α, β, and γ bands, whereas scalp EEG was better protected from such interference due to its active electrode design. Overall, this study indicates that while ear-EEG has natural resistance to eye-related artifacts, it is particularly sensitive to artifacts associated with jaw and head movements. Therefore, enhancing the robustness of ear-EEG in dynamic environments requires hardware improvements such as soft-fitting designs, wireless data transmission, and active shielding circuits, complemented by optimized advanced filtering algorithms.

In the third study[2], researchers quantitatively assessed the signal quality differences between ear-EEG and scalp-EEG when recording four auditory event-related potentials (N100 attention processing, MMN passive bias, P300 conscious counting, and N400 semantic processing) in a mobile environment. Researchers induced target ERPs using four standardized auditory paradigms, employed a 96-channel cap system to retain 12 electrodes around both ears (R1–R6/L1–L6) to simulate ear-EEG, and set up three preprocessing pipelines. The experimental results showed that ear-EEG could clearly record all ERP components, with waveform timing highly similar to scalp-EEG, and its average effect size reached a moderate level (*g*≈0.2–0.5). The group-level effect size (*g*>0.8) even surpassed that of standardized scalp processing; Compared to individualized optimal scalp EEG, bilateral ear-EEG exhibits 21%–44% signal loss (with the greatest loss in N100 and the least in N400), and unilateral configurations result in increased loss of 29%–50%; optimal ear-EEG channels for participants show significant individual variability and lack spatial regularity, validating the necessity of multi-channel fusion and individualized electrode selection. In summary, ear-EEG is suitable for mobile BCI and natural state monitoring scenarios due to its comfort, portability, and resistance to eye movement artifacts; however, its sensitivity to jaw/head movement artifacts results in signal fidelity that is still inferior to scalp-EEG. For high-fidelity whole-brain coverage requirements (e.g., semantic decoding), scalp-EEG is recommended; for long-term monitoring prioritizing concealment, ear-EEG with flexible electrode design, adaptive filtering, and individualized channel optimization can provide an effective solution.

In conclusion, Scalp-EEG demonstrates excellent resistance to motion artifacts during walking. Mechanical artifacts only occur at high speeds (e.g., 4.5 km/h) and can be effectively suppressed using algorithms such as ASR. Ear-EEG inherently resists eye movement artifacts but is significantly distorted by mandibular/head movements. ERP studies confirm that ear-EEG has

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moderate signal capture capability (*g* ≈ 0.2–0.5), but signal loss reaches 21%–44% compared to optimized scalp EEG. Although scalp EEG remains the preferred option for high-fidelity applications, the portability of ear EEG supports mobile monitoring. When enhanced with technologies such as soft-fitting hardware, adaptive filtering, and personalized channel optimization, it can effectively mitigate motion artifacts.

5. Comparison of Ear-EEG and Scalp-EEG Applications

5.1. Comfort comparison

Scalp EEG typically uses wet electrodes that require conductive gel to ensure good contact. However, the gel hardens as it dries, which may irritate the skin of the wearer and make it inconvenient for the wearer to clean their hair. The average wear tolerance time is typically no more than 2 hours, and signal quality deteriorates significantly after the gel dries [1]. Additionally, scalp EEG electrodes often need to be secured by adhering to the bridge of the nose or forehead. When pressure exceeds 10 kPa, up to 80% of participants experience itching discomfort. Combined with the device weight typically exceeding 50 g, this can more easily interfere with daily activities [7]. In contrast, intra-aural EEG electrodes often use dry electrode designs, such as silver-coated fabrics, enabling stable long-term recording of EEG signals without conductive gel [6][7]. Related studies indicate that gold-coated dry electrodes maintain good contact and signal quality even after continuous wear for ≥ 40 hours [1]. Since the ear canal is a moderately sensitive area with a pressure discomfort threshold (PDT) of 15–25 kPa, only approximately 15% of users report noticeable foreign body sensation; ear EEG devices typically weigh between 10–20 g, offering a wearing experience similar to ordinary earplugs and causing minimal disruption to daily activities [1][7]. In summary, intra-aural EEG offers significant advantages over scalp EEG in terms of no gel stimulation, lightweight design, and high tolerability.

5.2. Wearability comparison

While scalp EEG performs excellently in research, its portability is severely limited due to the inclusion of bulky amplifiers and multi-channel cables, restricting its use to laboratory settings [1]; The installation process requires professional assistance, taking 8–15 minutes, and cables are prone to tangling [7]; additionally, headband-style designs are conspicuous, making them unsuitable for discreet use in social settings [1][7]. In humid or sweaty conditions, electrode-skin contact quality deteriorates, leading to signal failure [6]. In contrast, ear EEG adopts a miniaturized design, integrated into earbuds resembling consumer-grade headphones, allowing users to complete self-installation in under 5 minutes [1][6]; its high portability enables application in various mobile scenarios such as walking or driving [1], and its high concealability results in user acceptance rates approximately 45% higher than traditional scalp EEG [7]. Additionally, since ear EEG effectively prevents sweat interference, it can operate stably in humid and hot environments [6]. In summary, ear EEG offers significant advantages in terms of portability, installation efficiency, and discreetness, making it more suitable for daily use scenarios.

5.3. Practicality Comparison

In terms of practicality, scalp EEG has a higher signal-to-noise ratio (15–20 dB) and multi-channel (8–64 channels) whole-brain coverage, making it more advantageous for supporting advanced cognitive tasks (such as N400 semantic decoding) and playing a role in clinical diagnosis and high-precision research [1][7]. In contrast, while ear EEG has a lower signal-to-noise ratio (8–12 dB) and is typically limited to single or dual channels focused on the temporal lobe, unable to cover the frontal lobe, its close-fitting design inherently resists motion artifacts in dynamic scenarios, enabling stable signal acquisition during activities like walking without

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additional noise reduction algorithms [6][7]. In terms of task performance, ear EEG achieved accuracy comparable to scalp EEG (T7/T8 electrodes) in emotion classification (71.07% vs. 69.85%), but its performance decreased by approximately 44% in higher-order cognitive tasks such as semantic decoding, with significant signal loss [6][7]. Therefore, ear EEG is more suitable for long-term continuous monitoring scenarios such as sleep monitoring, epilepsy warning, and fatigue detection, while scalp EEG has advantages in research and clinical applications requiring fine spatiotemporal resolution and high-fidelity measurements [1].

6. Conclusion

Despite various issues, Ear-EEG can effectively capture key auditory ERPs and alpha rhythms; its exceptional comfort and portability address long-standing usability barriers of Scalp-EEG. However, unresolved limitations of Ear-EEG persist: spatial coverage limits whole-brain monitoring; jaw movement artifacts reduce performance in dynamic environments; and channel optimization requires individualized calibration. Future research should prioritize: multi-electrode in-ear array designs to enhance spatial resolution; soft, biocompatible materials to enhance motion robustness; and adaptive filtering algorithms targeting gamma-band artifacts. In clinical applications, Ear-EEG shows promising potential for dynamic neurophysiological tracking (e.g., epilepsy, fatigue monitoring), while Scalp-EEG technology remains indispensable for high-precision research.

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