

REVIEW ARTICLE

Hearables: Bioelectronics technological challenges and opportunities

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Abstract

Wearable devices placed in or around the ear, often referred to as hearables, are gaining attention as alternative tools for pseudo-continuous health monitoring. Among their several capabilities, hearables are primarily useful for monitoring brain activity electronically via electroencephalography (EEG), enabling noninvasive, long-term recording of neural signals (e.g., from the ear canal). In addition to EEG, hearables can monitor heart rate, oxygen saturation, and temperature, all while maintaining the comfort and discretion of everyday items like earplugs or headphones. This review explores recent progress in combining multiple sensors, leveraging artificial intelligence (AI), and developing novel materials that make hearables more accurate, practical, and comfortable. On-device AI enables real-time, personalized insights that can support therapeutic interventions for neurological disorders like epilepsy. We seek further improvements in design and materials beyond this proof-of-concept, including three-dimensional printing with flexible electrodes while maintaining the unique property of monolithic circuit integration during system printing. That helps devices conform even better to the ear's anatomy for enhanced comfort and signal quality, while the rigidity of the main structure ensures a highly durable and reliable product suitable for everyday life. In particular, personalization through additive manufacturing enables custom-fitted hearables based on each user's unique ear canal features, supporting long-term wearability and reliable EEG acquisition. This review also addresses key challenges like motion artifacts and miniaturization, and current strategies to overcome them. Overall, this review highlights hearables as a key emerging technology, especially for EEG-based brain monitoring, offering a personalized, continuous, and noninvasive approach to future healthcare.

1. Introduction

In recent years, the increasing prevalence of chronic diseases and the need to achieve a healthier life have highlighted the need for long-term daily monitoring. Conditions such as cardiovascular diseases (Brieger et al., 2018), diabetes (Azhar et al., 2020), epilepsy (Logar et al., 2008), and mental health disorders (Gomes et al., 2023), among others, often require continuous tracking to ensure optimal management and timely intervention. These diseases can be unpredictable, with symptoms fluctuating throughout the day, making monitoring patients consistently over extended periods essential. Traditional healthcare systems

rely on periodic check-ups and episodic data collection, which may fail to capture the dynamic nature of these conditions.

To enable long-term health monitoring, wearable devices, such as smartwatches (Perez et al., 2019), fitness trackers (Evenson et al., 2015), smart rings (Lee et al., 2019), smart glasses (Soon et al., 2020), and hearables (Ne et al., 2021), have been increasingly utilized to continuously monitor the physiological signals of users for medical and wellness applications. These devices offer real-time tracking of vital signs, activity levels, and other biometrics, facilitating remote healthcare and early detection of health conditions.

The collection of biosignals holds paramount importance, given their potential to facilitate the diagnosis and treatment of a range of medical conditions (Kaniusas, 2011; Semmlow, 2018). By harnessing pseudo-continuous biosignals, it becomes feasible to assess the current state of diseases and obtain valuable feedback regarding the effectiveness of ongoing therapeutic interventions (Kaniusas, 2011). The imperative drives the rapid development of wearable devices to supervise high-risk patients, gather information on users' daily activities and health conditions, detect diseases in their early stages, and reduce healthcare costs (Yetisen et al., 2018). Among wearable devices, hearables are increasingly gaining popularity, in particular for brain sensing, due to their noninvasive nature, unobtrusive design, reliable fixation capabilities, and wearability around or inside the human ear or ear canal (Masè et al., 2020). Heart rate and accelerometer/gyroscope sensors rank among the most commonly integrated features in hearables, according to market research (Plazak and Kersten-Oertel, 2018). A survey conducted in 2014 revealed that a significant proportion of subjects, ~62% carry an earphone with them daily, making it the second most commonly carried device (Byrne, 2014). This data underscores earphones' daily use and popularity as portable audio devices, which holds the potential for electronic sensing. It also highlights the social acceptance of wearing earphones or earplugs in public spaces, indicating that people may be uncomfortable using bulky and strange electroencephalogram (EEG) devices.

Hearables, introduced by Nick Hunn (Hunn, 2014), were initially designed to measure biosignals within the ear canal, making them a unique wearable technology for healthcare and wellness applications. These devices represent the convergence of audio technology and wearable sensing or stimulation, allowing users to enjoy traditional audio functions while simultaneously benefiting from advanced health monitoring sensors (Plazak and Kersten-Oertel, 2018). This is particularly beneficial for brain sensing due to the anatomical location of the ear as well as the aforementioned wearability advantages, including ease of use, portability, and comfort, making hearables an attractive option for continuous health monitoring.

One of the key advantages of hearables over other wearable technologies is their ability to support long-term monitoring without compromising user experience (Masè et al., 2020). Positioned within the ear canal, hearables can continuously and unobtrusively capture physiological signals, such as EEG, heart rate, and temperature (Masè et al., 2020). This makes them particularly well-suited for monitoring chronic conditions and providing real-time health insights. However, the trade-off is that their signal quality may not always match that of clinical-grade devices specifically designed for high-precision monitoring (Masè et al., 2020). Additionally, unlike traditional wearable devices that require visible attachments to the body, hearables offer a more discreet and socially acceptable alternative, reducing potential discomfort or self-consciousness for users.

A conceptual illustration of the hearable vision is presented in [Figure 1](#).

Despite this, the ability of hearables to provide long-term, real-time data makes them ideal for applications where comfort and convenience are paramount, such as in the management of sleep disorders, brain-computer interfaces (BCIs), and mental health monitoring. For instance, they can be used to monitor EEG signals related to sleep patterns, offering users a noninvasive method to track their sleep quality over extended periods (Nakamura et al., 2019).

In comparison with other wearable technologies, such as smartwatches and fitness trackers, hearables are uniquely suited for sensing brain signals, particularly EEG. While devices like smartwatches typically focus on cardiovascular metrics such as photoplethysmography (PPG) or electrocardiography (ECG), the ear is not an optimal site for these modalities due to anatomical and signal quality limitations. Instead,

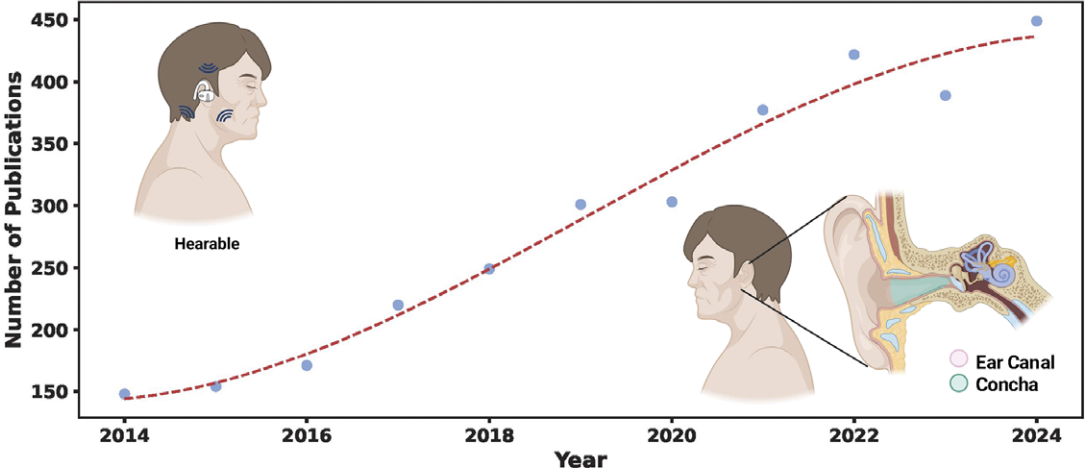


Figure 1. Hearables represent a promising direction for wearable technology by leveraging the unique anatomical features of the ear, such as the concha and ear canal. These regions support discreet, comfortable, and stable sensor placement, enabling long-term physiological monitoring. The increasing research interest in ear-based wearables underscores their potential for personalized, low-power, and socially integrated health solutions.

hearables are primarily designed for EEG acquisition, offering low spatial resolution brain signal monitoring in a compact and discreet form factor. This allows for comfortable, all-day wear without attracting attention or requiring special adjustments (Joyner et al., 2024). Although ECG and PPG can also be recorded by hearables, these signals are typically used as auxiliary data to support context-aware interpretation of EEG. A comprehensive comparison of hearables and other wearable technologies, including their respective sensing capabilities, advantages, and limitations, is provided in Table 1. In addition to their suitability for EEG sensing, hearables also benefit from the unique acoustics of the ear canal, which offer a stable and unobtrusive site for long-term monitoring with minimal motion artifacts compared to wrist- or chest-worn devices (Masè et al., 2020). Looking forward, hearables are expected to evolve beyond single-modality EEG acquisition toward multimodal integration, combining neural signals with acoustic input, motion sensing, and auxiliary physiological data to enable richer context-aware health and cognitive monitoring. Future directions also include the development of personalized

Table 1. Comparison of standard, wearable, invasive, and hearable devices for brain signal sensing

	Standard ^a	Other wearables ^b	Invasive ^c	Hearable
Portability	Poor	Medium	Excellent ^d	Good
Battery life	Plugged-in	Low (hours)	Varies ^e	Enough (a day)
Wear comfort	Very low	Low to medium	n/a ^f	High
Ease of use and wear	Difficult	Easy	n/a ^f	Easy
Cost	High to very high	High	Very high	Low
Long-term use (months)	Very limited	Limited	Excellent	Good

^aStandard refers to clinical-grade systems, such as traditional scalp or surface EEG in all forms of wet or dry electrodes.
^bOther wearables refer to wearable devices other than hearables, such as research-grade EEG, mainly in dry electrodes form.
^cInvasive refers to the invasive device, such as long-term brain implants (e.g., NeuraLink device) or endovascular electrocardiography, ECoG (e.g., Synchron’s Stentrode), or short-term intracranial electroencephalography (iEEG), also known as ECoG.
^dMainly depends on the external companion of an implantable brain interfacing device. For example, NeuraLink’s device does not have a companion that needs to be worn continuously, or Synchron’s device’s external companion sits on the patient’s chest.
^eSome brain (recording or sensing) interfacing implants are battery powered with recharge capability (e.g., NeuraLink’s device with more than 1,000 electrodes), but many are harvesting energy from a source outside the body (e.g., radio-frequency energy harvesting solution), which means there is no internal battery.
^fFor invasive brain interfacing solutions, this mainly relates to the wearable companion device or external unit, which is placed right above the implanted device – either magnetically or using skin adhesive – in an easy and not complicated way.

ear-mold manufacturing, ultra-low-power on-device artificial intelligence (AI), and clinical validation frameworks, which will be critical to advancing hearables from research prototypes to widely adopted health technologies.

EEG is a technique used to record the brain's electrical activity through electrodes placed on the scalp or at alternative sites such as the ear canal (Henry, 2006). It is widely used in both clinical and research settings for monitoring brain states, diagnosing neurological disorders, and studying cognitive processes. Recent advancements have enabled the miniaturization of EEG systems, making it feasible to integrate EEG sensing into wearable and hearable devices for continuous, unobtrusive brain monitoring in real-world environments (Looney et al., 2012). Conditions such as epilepsy and sleep disorders often require long-term EEG monitoring; however, conventional clinical EEG setups can be cumbersome and disruptive to daily life (Rosenow and Lüders, 2001). In contrast, ear-EEG provides a comfortable and discreet alternative, offering the potential for extended brain monitoring outside clinical settings with minimal impact on the user's routine (Looney et al., 2012). To enable this, our approach emphasizes the personalizability of ear-EEG electrodes through additive manufacturing, allowing the entire electronic system to be fabricated according to the unique anatomical features of each user's ear canal.

Overall, hearables present a promising avenue for healthcare applications, bridging the gap between traditional audio functions and advanced biosignal monitoring, and offering a versatile, user-friendly option for continuous health data collection.

In this article, we survey a range of techniques and devices developed in the context of hearables for brain sensing and vital signal monitoring, with particular emphasis on their form factors, signal quality, and suitability for long-term, real-world use. Our review encompasses both current technologies and emerging directions, highlighting opportunities for future development in the field of hearable health monitoring. To identify relevant literature, we performed a structured search across databases including PubMed, IEEE Xplore, and Google Scholar. Search terms included “hearable EEG,” “hearable biosensing,” and “ear EEG.” We prioritized peer-reviewed publications from the past decade that addressed either the technical performance or the practical usability of hearable systems in everyday environments.

2. Current applications

Hearables have evolved beyond their original role as audio devices and are now being repurposed as advanced platforms for health monitoring, with ear-EEG emerging as the most prominent application. These in-ear wearable technologies integrate biosensors that allow for continuous, unobtrusive collection of physiological signals in a user-friendly form factor. Their unique placement within the ear canal makes them especially well-suited for capturing brain activity, enabling applications in sleep staging, cognitive workload monitoring, and BCIs (Holtze et al., 2022; Zhou et al., 2023). Among various sensing modalities, ear-EEG stands out for its ability to support long-term neural monitoring in real-world environments, offering a compelling alternative to traditional scalp EEG systems.

2.1. Ear-EEG

Ear-EEG technology stands out by recording EEG signals from within the ear canal, representing a significant departure from traditional scalp EEG methodologies. Conventional scalp EEG requires an extensive setup process involving substantial time, bulky equipment, and limited suitability for daily wear. In contrast, ear-EEG offers an innovative, robust, discreet, and noninvasive solution for monitoring brain activity in real-world, non-laboratory settings (Mikkelsen et al., 2015). This approach has gained increasing attention for its ability to capture EEG signals directly from the ear canal. However, the anatomical variability of the human ear poses significant challenges to the use of standardized ear-EEG electrodes, often resulting in inconsistent signal performance. Therefore, electrodes must either be flexible enough to conform to individual ear canal shapes or be manufactured in customized geometries. While wet electrodes remain the gold standard for EEG signal quality, their reliance on conductive gel

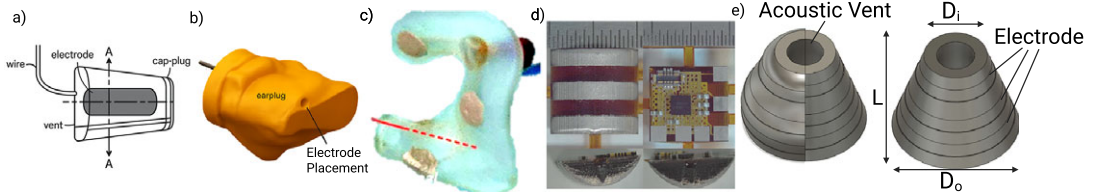


Figure 2. Various types of ear EEG electrodes have been developed in the field. (a) Generalized electrode design based on a common ear-hub (Kidmose et al., 2013). (b) Earhub-style electrode produced by molding (SintotSKIY and Hinrichs, 2020). (c) Earhub-style electrode with an integrated auricle holder (Looney et al., 2014). (d) Single-piece design combining the ear electrode and circuit board (Our ear-EEG) (L Yu et al., 2024). (e) 3D model of the integrated electrode and circuit board, featuring adjustable parameters including D_o (outer diameter), D_i (inner diameter), and L (length), as well as customizable electrode shape and curvature. This design enables on-demand manufacturing tailored to individual anatomies across different age groups and genders. The rigid structure ensures a durable and reliable product suitable for everyday life, for example, if the device drops on the ground or is pressed a little bit while in the pocket, and so forth.

makes them impractical for daily wearable use. Dry electrodes are more convenient but often suffer from signal degradation due to high skin impedance. Recent developments in semi-dry electrodes, such as hydrogel-coated designs, present a promising compromise, although further research is required to ensure their long-term stability and comfort (Ge et al., 2023). Figure 2 presents representative examples of current ear-EEG electrode designs, highlighting key variations in form factor, integration, and personalization.

To address these issues, generalizable ear-EEG electrodes have been developed to fit everyone. Such electrodes are typically constructed from elastic materials, enabling them to compress and expand to conform to the unique shape of an individual's ear canal. This adaptability ensures a secure fit, enhancing signal quality and user comfort during prolonged use. This approach is favored due to its straightforward manufacturing process, which simplifies production while offering a “one-size-fits-all” solution. For instance, one design utilizes a foam substrate to allow the ear-EEG electrode to adapt to the shape of the ear canal, improving fit and signal stability (Goverdovsky et al., 2017). This design features two electrodes and two microphones for applying stimulation. The choice of material effectively mitigates motion artifacts arising from both minor and substantial mechanical deformations of the ear canal walls (Goverdovsky et al., 2017). This electrode design also incorporates the use of two microphones to capture acoustic signals traversing through dense head tissues and uses these signals. Another design utilized conductive silver fabric, foam earplugs, heat-shrinkable tubing, and copper wire to construct a generalized electrode (Juez et al., 2021). To address the issue of long manufacturing time and short lifespan for personalized ear-EEG electrodes, Liang et al. developed a method using impressions to manufacture a generalized ear-EEG based on the average measurements of the ear at three critical dimensions: the aperture, isthmus, and length (Liang et al., 2023).

Researchers have increasingly employed three-dimensional (3D) printing technology to optimize EEG signal acquisition in the ear-EEG domain. By leveraging the capabilities of additive manufacturing, complex shapes can be created, enabling a precise fit within the ear canal for improved electrode contact and signal quality. Notable advancements include the work of Kaveh et al., who developed personalized wireless ear-EEG electrodes using 3D-printed molds combined with a silicone base (Kaveh et al., 2020). This approach allows for the fabrication of both customized and generalized electrodes. Similarly, Yu et al. introduced a 3D-printed ear-EEG device that integrates both the electrode and circuit board into a single printed structure (L Yu et al., 2024). This design has the potential to accommodate various ear shapes, enhancing usability across different individuals. Despite these innovations, the manufacturing process often requires additional steps, such as casting and chemical treatments, to apply conductive

materials, making production more complex. To address these challenges, an ear-EEG electrode with an extendable spiral structure was developed, using electrothermal actuation to conform to the unique geometry of an individual's ear canal (Z Wang et al., 2023). This design, which explores applications in visual and auditory BCIs, features a dual-layer structure composed of shape memory polymers (SMPs). The outer electrothermal actuation layer (EAL) facilitates expansion, while the EEG detection layer (EEGDL) consists of Au wires and insulating polyimide for signal acquisition. Upon heat activation, the electrode spirals outward, adapting seamlessly to the unique curvature of the auditory meatus for a customized fit. Further contributions to 3D-printed ear-EEG technology include Jeong and Jeong, who created ear canal impressions with moldable plastic beads and applied silver paste for conductivity, and Mikkelsen et al., who developed soft silicone earplugs with silver buttons and copper wire connections for automatic sleep staging (Mikkelsen et al., 2017; Jeong and Jeong, 2020). Additionally, Tabar et al. employed 3D printing to fabricate customized ear-EEG electrodes, enhancing both user comfort and signal accuracy (Tabar et al., 2021).

An alternative approach for creating personalized ear-EEG electrodes involves integrating standard electrodes into custom-moulded soft earpieces. One implementation employed a dry ear-EEG system featuring IrO₂-coated titanium electrodes embedded in elastic earmold silicone (Kappel et al., 2018). Another high-density configuration used 15 electrodes per ear to achieve signal quality comparable to, or even exceeding, that of scalp EEG in certain evaluations, such as auditory steady-state response (ASSR) and steady-state visual evoked potential (SSVEP), also utilizing IrO₂ as the electrode material (Kappel and Kidmose, 2017). In a separate design, a 3D-printed ear canal model was used to install six silver electrodes for objective threshold estimation tasks (Bech Christensen et al., 2018).

Various materials have been explored to enhance ear-EEG performance. One notable example involves a porous-structured platinum electrode specifically designed for ear-EEG applications, which achieved an impedance below 5 k Ω at 20 Hz under dry conditions (Eickenscheidt et al., 2020).

Additional technologies, such as around-Ear-EEG systems, have been developed to investigate optimal electrode placement. Bleichner et al. created an around-Ear-EEG system using several layers of biocompatible polyimide, with conductive components consisting of gold-plated ends, pure copper traces, and conductive Ag/AgCl-based polymer thick film ink (Bleichner et al., 2016).

After gathering the data from the electrode, it is necessary to preprocess the signal and convert the signal from the analog domain into the digital domain, and send it to a host device for further applications. An analog front end is often necessary to convert the analog signal into digital form to enhance the ear-EEG devices' portability. However, integrating the circuit board naturally and unobtrusively presents another challenge. Methods to reduce the device's visibility are required. To address visibility concerns, one approach involved placing the analog front-end (AFE) module at the back of a hat, thereby keeping the system unobtrusive while maintaining signal fidelity (Bleichner et al., 2015).

There is an emerging need to integrate the analog front end directly onto the printed electrode to further augment the functionality and discretion of ear-EEG electrodes. This approach minimizes the electrode's size and visibility while optimizing signal reception. Integrating the analog front end with the ear-EEG electrode makes it possible to achieve a less obtrusive and more efficient EEG recording system. This integration streamlines the manufacturing process and enhances the performance and user experience of ear-EEG technology.

Different sensors are also integrated into the ear-EEG piece to gather additional information for medical and research use. An in-ear integrated array of multimodal electrophysiological and electrochemical sensors has been developed to simultaneously sense EEG, Electrooculogram (EOG), and lactate concentration (Xu et al., 2023). This demonstrates the feasibility of integrating multiple sensors into a single device, enabling the collection of diverse biosignals. Such a multi-sensor approach enhances the device's capacity to provide comprehensive physiological data, facilitating advanced applications, such as personalized health monitoring, real-time diagnostics, and sophisticated data analysis, for medical and research purposes.

Seamlessly integrating the complete analog front end and the microcontroller (MCU) into a single earpiece to facilitate the wireless transmission of digital signals to a designated device remains a

substantial challenge in this field. This challenge is further accentuated by the necessity of minimizing the distance between the electrode and the analog front end and the size of the auditory meatus (Mozaffari et al., 2021). One suggested approach entails the strategic distribution of electrical components around the external ear rather than direct insertion into the ear canal (Kaveh et al., 2020). However, even with this approach, the visibility of these components remains noticeable, potentially causing social discomfort. In practical scenarios, this situation might require additional accessories, such as a hat, to effectively conceal the components.

It is important to acknowledge that while addressing this challenge entails inherent complexities, its resolution is attainable. Utilizing application-specific integrated circuits (ASICs) has emerged as a promising solution; however, it is pertinent to recognize that producing a limited quantity of ASICs can involve significant costs. As time progresses, the continued advancement of manufacturing and electronics technologies contributes to the ongoing miniaturization of electronic components. This enduring trend plays a pivotal role in facilitating the seamless integration of all necessary components within the confined space of the earpiece.

Ensuring that users can still capture environmental sounds is crucial for most electrodes. A hollow structure is often applied to ensure the patient can hear surrounding sounds effectively.

Table 2 compares various ear-EEG electrodes based on impedance, electrode material, signal type, and connectivity. The findings highlight that while dry electrodes improve convenience, wet electrodes still offer the best signal quality.

2.1.1. Applications for ear-EEG

Ear-EEG, owing to its portability and discreet nature, finds diverse applications in fields requiring long-term and daily EEG monitoring. For applications requiring extended daily use, ear-EEG offers a highly suitable solution. Its discreet, comfortable design makes it ideal for continuous wear, addressing the challenges of capturing data during unpredictable or infrequent events. Furthermore, ear-EEG devices are less intrusive compared to traditional scalp-EEG setups, enhancing user compliance over extended periods. One of the most common applications is in BCIs, which enable long-term control capabilities. For example, an ear-EEG system has been developed for BCI applications, utilizing SSVEPs as input for a speller (Z Wang et al., 2023). This technology holds promise for various assistive communication and control applications. Another system demonstrated the feasibility of using ear-EEG signals for BCI applications based on motor imagery EEG classification (Zhou et al., 2023).

In addition to BCIs, ear-EEG is also valuable in clinical and remote health monitoring settings. Seizure detection is one of the major applications for EEG; therefore, it is crucial for ear-EEG to be able to capture the seizure signal as well.

Joyner et al. demonstrated that ear-EEG can be routinely used for collecting complementary, prolonged, and remote neurophysiological data (Joyner et al., 2024). This capability is particularly beneficial for patients who require continuous monitoring outside of a clinical environment, offering a more flexible and less invasive alternative to traditional EEG methods. Thus, in the current study, demonstrating the capability of the device to capture seizure-related data is a crucial step toward advancing its development. This validation will establish the device's potential for applications in seizure detection and monitoring, laying the groundwork for future research and practical implementations.

Moreover, integrating ear-EEG with other devices has opened new avenues for research and practical applications. One approach combined ear-EEG with hearing aids to measure the ASSR for hearing threshold estimation (Sergeeva et al., 2024). This innovation enhances the functionality of hearing aids, enabling them to serve a dual role in both hearing assistance and neurophysiological monitoring. Another system utilized flexible brush-type electrodes in an ear-EEG device to collect both EEG and PPG signals for decoding auditory-evoked responses (Choi et al., 2023).

The utility of ear-EEG extends to home-based health applications as well. A generalized ear-EEG system has been developed for at-home sleep monitoring (Tabar et al., 2023). This system enables the collection of sleep data comfortably and unobtrusively, which is essential for accurate and naturalistic

Table 2. Comparison between different ear-EEG electrodes

References	Modality	Electrode number	Impedance (kΩ)	Sampling rate (Hz)	Electrode material	Dry/wet	Signal type	Data telemetry	Verification	Novelty
Goverdovsky et al. (2017)	EEG, ECG, motion artifacts	2	< 10	1,200	Cloth electrode with conductive thread	Wet	Analog	Wire	SSVEP ^a , ASSR ^b , VEP ^c , Alpha rhythm	Detect motion artifacts
Juez et al. (2021)	EEG	6	–	250	Conductive fabric of silver	Wet	Analog	Wire	Alpha rhythm	Electrode made of conductive fabric
Liang et al. (2023)	EEG		35 and 45	500	AgCl	Dry	Analog	Wire	Alpha rhythm, ASSR ^b , VEP ^c , MMN	Expression moulding by the average measurement of the ear
Wang et al. (2023)	EEG	3	< 134.27	–	Conducting Au wires and insulating polyimide (PI)	Dry	Analog	Wire	SSVEP ^a , auditory decoding	Extendable spiral structure that can adapt to the subject's ear
Ge et al. (2023)	EEG	1	< 3	1,000	HPMC in PVA matrix	Semi-dry		Wire	Attention of the testers	High-conductivity, low-impedance, and biologically adaptable hydrogel
Bleichner et al. (2016)	EEG	10	< 20	500	Ag/AgCl	Gel	Digital	BLE ^d	Attention modulation of the ERP	Around ear-EEG
Kappel et al. (2018)	EEG	6	435	500	IrO ₂	Dry	Analog	Wire	ASSR ^b , SSVEP ^a , Alpha rhythm	–
Kaveh et al. (2020)	EEG, EMG	4, 2 reference	–	–	Silver	Dry	Digital	BLE ^d	EOG, alpha rhythm, ASSR ^b	Generalized 3D printed silver dry electrode
Jeong and Jeong (2020)	EEG	1	–	250	Silver-coated plastic	Gel	Analog	Wire	PVT	–
Eickenscheidt et al. (2020)	EEG	4	< 5	512	Highly porous platinum	Dry	Analog	Wire	Alpha rhythm	Low impedance platinum dry electrode
Bech Christensen et al. (2018)	EEG	6	< 20	1200	Silver	Gel	Analog	Wire	ASSR ^b , PTA	–
Mikkelsen et al. (2017)	EEG	6 each ear	–	200	Silver	Gel	Analog	Wire	ASSR ^b , PSG	–
Lee et al. (2019)	EEG	2, 1 reference, 1 ground	–	1,000	–	Dry	Digital	BCC ^e	ASSR ^b	Wireless transmission using BCC
Kappel and Kidmose (2017)	EEG	15	–	500	IrO ₂	Saltwater	Analog	Wire	ASSR ^b , SSVEP ^a	Large electrode number
Y Xu et al. (2023)	EEG, EOG, lactate concentration	3 EEG, 1 Ref, 1 DRL	386	500	Stretchable silver (Ag) ink	Dry	Digital	BLE ^d	Alpha modulation, ASSR ^b , eye movement, lactate sensing	Multi-sensor ear-EEG

^aSSVEP, steady-state visual evoked potential.^bASSR, auditory steady-state response.^cVEP, visual evoked potential.^dBLE, bluetooth.^eBCC, body channel communication.

assessment of sleep patterns and disorders. The long-term monitoring capability of ear-EEG makes it an ideal tool for evaluating conditions, such as insomnia, sleep apnea, and other sleep-related issues. Additionally, a wireless ear-EEG device has been introduced for drowsiness detection, leveraging a previously developed ear-EEG platform (Kaveh et al., 2024).

Furthermore, ear-EEG has shown significant potential in various other medical and wellness applications. For instance, it has been demonstrated as a noninvasive, real-time tool for fatigue detection, enabling continuous monitoring and management of fatigue levels (MC Yarici et al., 2023). In epilepsy monitoring, ear-EEG systems have been developed to detect and record epileptic seizures, providing a more patient-friendly alternative to traditional EEG setups (Juez et al., 2021). Additionally, ear-EEG has been applied in the evaluation of fatigue in aviation contexts, supporting safety and performance monitoring in high-demand environments (Klaren et al., 2024).

Sleep staging is another area where ear-EEG has demonstrated its effectiveness. Mikkelsen et al. explored the use of ear-EEG for automatic sleep staging, which can significantly improve the diagnosis and treatment of sleep disorders by providing detailed and continuous sleep data (Mikkelsen et al., 2017). The long-term monitoring capability of ear-EEG is particularly advantageous in evaluating various medical conditions, including sleep disorders, cerebrovascular diseases, psychiatric conditions, and movement disorders (Tatum, 2001). Sleep scoring models have been developed based on data recorded from ear-EEG (Borup et al., 2023). Additionally, AI models trained on ear-EEG data have demonstrated high consistency with scalp-EEG-based scoring, supporting the feasibility of using ear-EEG in EEG-based AI applications, particularly in older adults (Hammour et al., 2024).

The versatility of ear-EEG positions it as a promising technology for a wide range of applications, from healthcare to assistive technologies and beyond. Its ability to provide continuous, noninvasive monitoring makes it an invaluable tool in both clinical and everyday settings, paving the way for advancements in personalized health care and neurotechnology.

These examples collectively highlight the broad range of applications for ear-EEG devices, emphasizing the critical importance of advancing their development to reliably and accurately capture EEG signals. Moreover, they offer valuable insights into potential avenues for further innovation and refinement in this technology.

2.1.2. Ear EEG recordings

The performance of ear-EEG has been evaluated in numerous studies, demonstrating that while its signal quality is generally lower than that of conventional scalp EEG, it remains sufficient for detecting reliable neural responses. This trade-off in signal fidelity is often considered acceptable given the substantial benefits of ear-EEG in terms of unobtrusiveness, comfort, and suitability for long-term, real-world monitoring.

Yu et al. validated the feasibility of ear-EEG for auditory stimulus detection using the ASSR paradigm (Yu et al., 2024). As shown in Figure 3, frequency-specific neural responses were clearly detected using

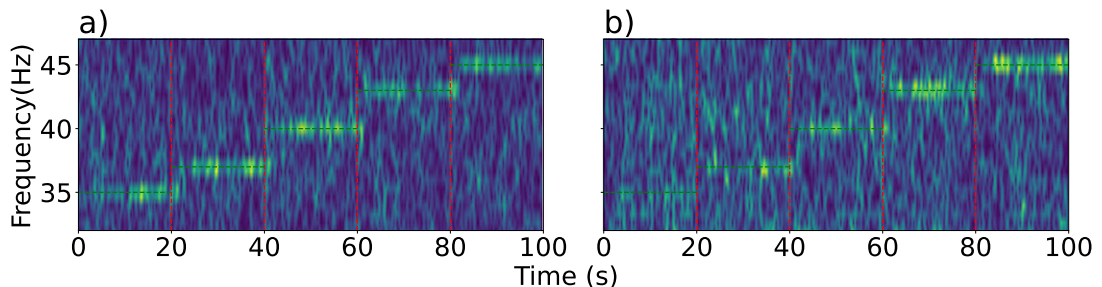


Figure 3. ASSR test using (a) scalp EEG and (b) ear-EEG. Red lines indicate the timing of frequency changes, while green lines mark the expected auditory response frequencies (Yu et al., 2024).

ear-EEG with wet electrodes, demonstrating a strong correspondence to responses captured via scalp EEG. In both modalities, green lines indicate the expected response frequencies, while red lines mark the time points of stimulus frequency changes.

To further evaluate the capabilities of ear-EEG, we analyzed data from the Ear-EEG Sleep Monitoring 2019 (EESM19) dataset (Mikkelsen et al., 2019). The recordings were collected using personalized dry IrO_x electrodes on 20 participants (7 males and 13 females) with an average age of 25.9 years (range: 23–36) (Bjarke Mikkelsen et al., 2025). A TMSi Mobita amplifier was used for signal acquisition. For the ASSR test, they were exposed to a 40 Hz amplitude modulated at 1 kHz auditory stimulus (Bjarke Mikkelsen et al., 2025). A corresponding neural response at 40 Hz was expected, representing the ASSR. Figure 4 shows the results across 20 subjects, comparing signal-to-noise ratio (SNR) measurements between scalp and ear-EEG. The SNR was defined as the power at 40 Hz relative to the average power within the 35–45 Hz band, excluding 40 Hz. Results demonstrate that ear-EEG consistently captured the 40 Hz ASSR, with performance comparable to that of scalp EEG.

These data collectively support the viability of ear-EEG as a practical and reliable alternative to traditional scalp EEG, particularly for auditory stimulus monitoring in wearable applications.

In-ear EEG systems were generally well tolerated, with most participants reporting comfort and ease of use, even during sleep recordings. Minor issues such as earpiece displacement or pressure around the tragus were occasionally reported, and intermittent Bluetooth interruptions occurred in some cases (Moumane et al., 2024). In contrast, scalp EEG often requires gel application and can cause discomfort over extended recordings, suggesting that in-ear EEG may offer advantages for long-term or ambulatory monitoring (Moumane et al., 2024). Dry in-ear electrodes exhibited initially high impedance (~900 kΩ) that decreased and stabilized over ~3 h (~290 kΩ at 50 Hz), comparable to other state-of-the-art dry electrodes. While scalp electrodes with gel maintain low impedance throughout, in-ear EEG achieves sufficient contact over time to ensure signal quality, highlighting its potential for prolonged, unobtrusive recordings. In-ear EEG successfully captured key rhythms, such as alpha, theta, spindles, and slow waves, with waveforms temporally aligned with scalp EEG. However, amplitudes were generally lower, about two times smaller for alpha waves, and fluctuations were slightly higher during naps due to movement or intermittent contact loss. Artifact prevalence was minimal during controlled alpha tests but increased during sleep, particularly with earplug displacement (Moumane et al., 2024). Scalp EEG generally shows higher amplitude and more stable RMS values, but requires more preparation and is less comfortable. In-ear EEG reliably detected alpha peaks during eyes-closed conditions, although power was roughly half that of scalp recordings. SNRs were slightly lower, but correlations with scalp signals were high (93% of subjects), especially over temporal regions. Across sleep stages, relative spectral power in-ear closely matched scalp EEG, with small differences in alpha, delta, and beta1 bands during Wake. Correlations strengthened during deep sleep (N3), indicating coherent slow-wave activity in both modalities (Moumane et al., 2024).

Ear-EEG demonstrates good temporal and spectral fidelity compared to scalp EEG, despite amplitude reductions and occasional susceptibility to artifacts. It is particularly promising for applications requiring long-term or ambulatory monitoring, where comfort and ease of use are critical (Moumane et al., 2024). Scalp EEG remains superior in terms of absolute signal amplitude and stability, but in-ear EEG offers a practical trade-off between usability and recording quality (Moumane et al., 2024).

2.2. Other applications

While ear-EEG remains the focus of most neurotechnology efforts, hearables have also been explored for other biosignals. Ear-ECG captures cardiac activity and may support heart rate variability analysis or arrhythmia detection. Ear-PPG allows for blood oxygenation and heart rate monitoring, particularly in cardiovascular applications (Ferlini et al., 2021). Additionally, in-ear temperature sensing enables continuous core body temperature tracking for fever detection and wellness monitoring (Olson et al., 2023). Despite this diversity, the growing interest in ear-EEG underscores its potential as a cornerstone of hearable-based neurotechnology, offering both clinical utility and everyday usability (Ne et al., 2021).

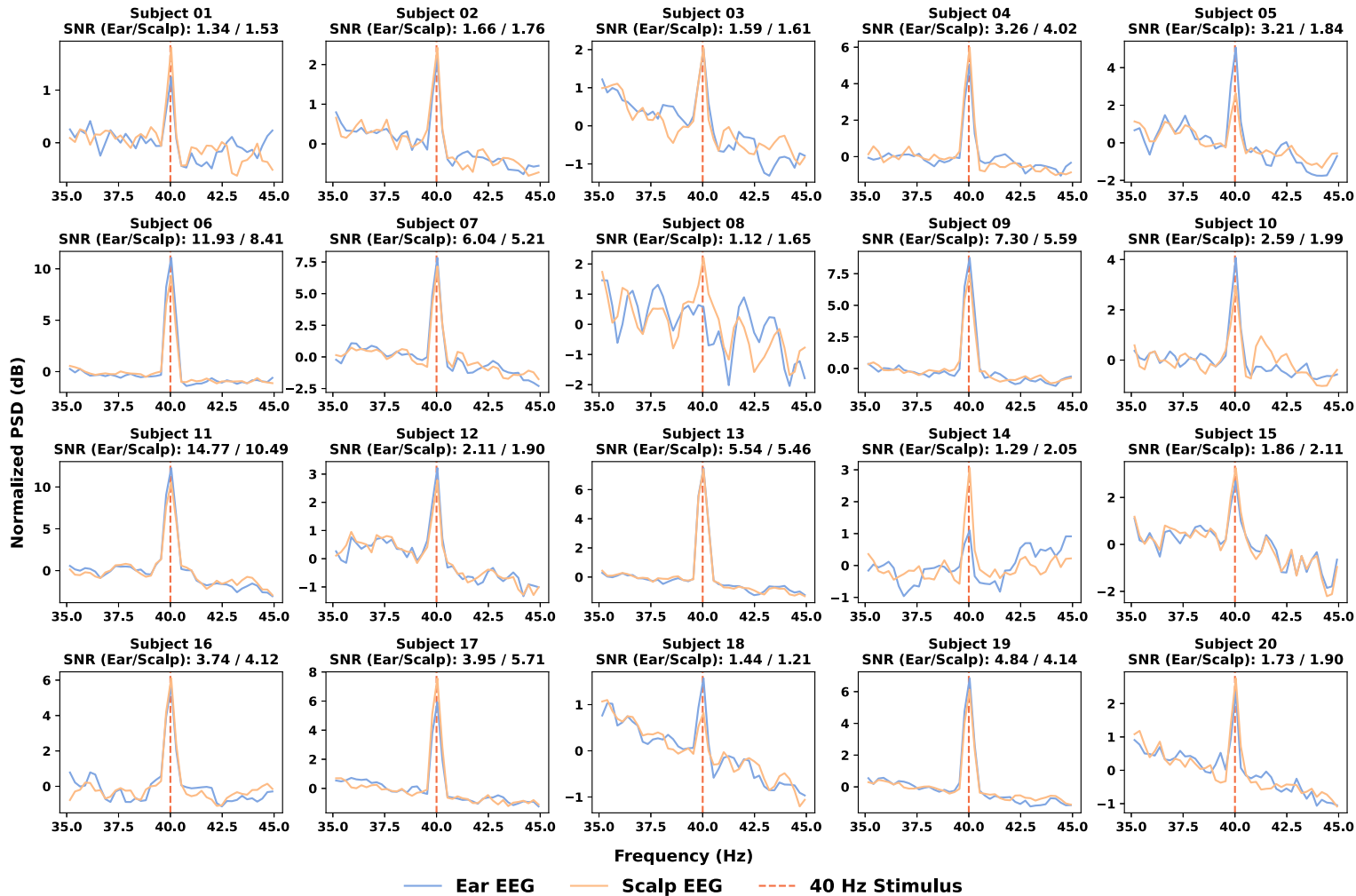


Figure 4. Comparison of ASSR test results between scalp EEG and ear-EEG across 20 subjects from the EESM19 dataset, where the signal-to-noise ratio (SNR) is defined as the power at 40 Hz relative to the average power in the 35–45 Hz band, excluding 40 Hz (Mikkelsen et al., 2019).

2.2.1. *Ear-ECG*

ECG is a pivotal medical technology designed to capture and document the electrical potentials generated by the rhythmic contractions of the human heart (Goldberger and Gold-berger, 1981). ECG plays a crucial role in the investigation and diagnosis of various cardiac conditions, most notably cardiac arrhythmias. Additionally, it serves as a fundamental tool for detecting and evaluating a range of cardiac disorders, including critical conditions, such as myocardial infarction, commonly known as a heart attack (Meek and Morris, 2002). Consequently, long-term self-monitoring with wearable ECG devices is rapidly evolving, facilitating continuous monitoring of cardiac health (Smital et al., 2020).

Like hearable EEG, hearable ECG devices also encounter challenges related to motion artifacts that can affect signal quality (Bouzid et al., 2022). These artifacts, often induced by physical movements, pose a challenge to accurately capturing ECG signals. Therefore, addressing motion artifacts is a critical aspect of designing reliable hearable ECG systems.

Wearable ECG devices are typically classified into two primary categories: patches, which are affixed near the chest, and smartwatches, which are worn on the wrist (Bouzid et al., 2022). These varied device types provide users with a spectrum of options for monitoring their cardiac health, ranging from more conventional handheld devices to inconspicuous and continuous monitoring solutions in the form of patches and smartwatches.

While ear-based ECG monitoring might not be the predominant trend, it remains a viable and promising choice. Previous research has shown a significant degree of waveform similarity between the reference arm-ECG and the ear-ECG recorded from the ear canal (Hammour et al., 2019). This finding suggests that monitoring ECG from the ear canal can offer a feasible and reliable alternative for cardiac health monitoring. The development by Von Rosenberg et al., in particular, is noteworthy as it presents an innovative method for ECG detection within the ear canal (Von Rosenberg et al., 2017). This novel approach employs a combination of conductive fabric electrodes and microphones as sensing components, enabling cross-correlation techniques for ECG signal extraction. The fundamental principle underlying this technique involves using microphones to capture subtle pulsations within the blood vessels located in the ear canal. Subsequently, advanced signal processing algorithms are applied to the microphone-recorded data to detect specific components of the ECG waveform, such as the QRS complex (Von Rosenberg et al., 2017). This development opens up exciting possibilities for ECG monitoring using hearable devices and has the potential to revolutionize the field of cardiac health monitoring.

2.2.2. *Ear temperature*

Temperature is undeniably a critical parameter that serves as a key indicator for identifying potential infections (Levander and Grodzinsky, 2017). Additionally, it plays a fundamental role in continuous health monitoring. Notably, temperature monitoring finds important applications in outdoor working environments, including among athletes, where it helps prevent individuals from experiencing adverse health effects due to extreme temperature conditions (M Huang et al., 2016). Beyond this, temperature monitoring extends to the analysis of body temperature rhythm and circadian rhythms, which have associations with various health conditions, including hormonal function, mental health, and gastrointestinal complaints (Vitaterna et al., 2001).

In the realm of temperature measurement, infrared ear thermometers are widely used for assessing temperature within the ear canal. A notable advancement includes the development of a hearable temperature sensor that also incorporates sweat detection and audio output capabilities (Matsumoto et al., 2019). This multifunctional device enables the identification of individuals at risk of heat stroke, facilitating timely intervention and improved patient care (Matsumoto et al., 2019). The integration of temperature sensing within hearables significantly enhances their health-monitoring capabilities. Additionally, the embedding of ear temperature sensors into hearing aids has been explored to support continuous temperature monitoring (Olson et al., 2023).

2.2.3. Ear-PPG

Oxygen saturation is a vital physiological metric, signifying the proportion of oxygen-bound hemoglobin to unbound hemoglobin in the bloodstream (Hafen and Sharma, 2018). It holds substantial importance in diagnosing various medical conditions. For instance, it is crucial in the detection of sleep apnea, a condition where oxygen saturation levels can significantly fluctuate during episodes of interrupted breathing (HJ Davies et al., 2020). Additionally, as the global prevalence, morbidity, and mortality of chronic obstructive pulmonary disease (COPD) continue to rise (López-Campos et al., 2016), continuous monitoring of oxygen saturation becomes invaluable for the timely identification and management of life-threatening COPD exacerbations (Clarke et al., 2015).

Among the vital parameters used in health monitoring is blood pressure. Hypertension, characterized by elevated blood pressure, is one of the primary conditions associated with cardiovascular health and can often develop without presenting apparent symptoms, making regular monitoring crucial for early intervention (Zhang et al., 2017). PPG is also widely applied for measuring blood pressure. Commercial clinical PPG sensors are commonly placed on the finger, earlobe, and forehead (Mendelson and Pujary, 2003).

PPG sensors are a standard method for noninvasive detection of oxygen saturation levels, also known as SpO₂ (Hafen and Sharma, 2018). These sensors function by emitting light from an LED into the body tissues. Unlike EEG or ECG, which measure biopotentials, PPG sensors measure the amount of light absorbed by these tissues, a quantity that varies with changes in oxygen-bound hemoglobin. This, in turn, allows for the calculation of SpO₂ values (Budidha and Kyriacou, 2018).

In the context of wearable PPG, sensors can be placed in various locations on the body, including the fingertip, earlobe, wrists, forearm, ankle, forehead, and torso (Budidha and Kyriacou, 2018). Importantly, in-ear PPG sensors have demonstrated enhanced reliability in complex monitoring environments compared to conventional finger-based PPG sensors (Budidha and Kyriacou, 2018). The choice of the ear as a measurement location offers distinct advantages, primarily because ear-based PPG sensors are less susceptible to motion artifacts, a common source of noise that can affect signal quality during monitoring (Castaneda et al., 2018).

Researchers have made significant strides in the field of ear-PPG technology. One notable advancement is a compact ear-PPG system featuring a $16 \times 4 \times 3.2 \text{ mm}^3$ (length $\times$ width $\times$ height) board and a PPG sensor designed for integration into an earplug (Pedrana et al., 2020). This innovative technology incorporates accelerometers to mitigate the influence of motion-induced interference, following a common practice in other hearable technologies (Pedrana et al., 2020). These advancements open promising opportunities for unobtrusive and reliable monitoring of oxygen saturation and related physiological parameters.

2.2.4. Chemical sensing

Chemical sensors, such as sweat sensors, have also been developed for gathering additional physiological information from the ear. The literature in this field is very limited, as eccrine glands are sparse in the ear (Streckfus, 2022). Consequently, the integration of sweat-based chemical sensors in ear-worn devices (hearables) remains challenging, and only a few studies have attempted such applications. For example, a hearable device can sense core body temperature, sweat rate, and sweat or interstitial sodium ion (Na⁺) concentration for early detection and prevention of heat stroke (Matsumoto et al., 2019). Beyond heat-related monitoring, chemical sensing utilizing electrochemical electrodes in hearables can provide insights into hydration status, electrolyte balance, and metabolic changes, enabling personalized health feedback in real time. Recent studies have demonstrated in-ear biochemical sensing platforms that integrate ion-selective electrodes and microfluidic sampling for continuous sweat monitoring, highlighting their potential to capture dynamic electrolyte variations under exercise or thermal stress conditions (Matsumoto et al., 2019). Moreover, a multimodal ear-worn system has been developed that combines sweat lactate sensing with ear-EEG acquisition, enabling simultaneous metabolic and neural monitoring (Y Xu et al., 2023). Such integration paves the way for long-term,

unobtrusive health monitoring and offers opportunities for early detection or progression tracking of neurodegenerative diseases.

3. Current challenges

While hearable technologies have achieved significant advancements, several key challenges continue to impede their performance, usability, and scalability. The literature in this field is very limited, as eccrine glands are sparse in the ear (Streckfus, 2022). Consequently, the integration of sweat-based chemical sensors in hearables remains challenging, and only a few studies have attempted such applications. One major obstacle is the anatomical variability of the auditory meatus, particularly its curvature, which complicates the design of universally fitting devices and affects consistent sensor placement across users. Motion artifacts caused by jaw movements, head shifts, or external disturbances further compromise signal integrity and reliability. Moreover, strict design constraints and the demands of miniaturization make it challenging to integrate advanced components within the compact form factor required for hearables. Overcoming these barriers is crucial for the development of the next generation of robust, user-friendly, and clinically viable devices. The primary challenges are illustrated in Figure 5.

3.1. Variance auditory meatus curvature

To accurately capture EEG signals, it is essential to position multiple EEG channels in close proximity to the patient's auditory meatus. However, due to the inherent anatomical variability of patients' auditory meatus, innovative solutions are required to address this challenge.

Various approaches have been explored in response to this challenge. A notable strategy involves utilizing 3D scanning technology to meticulously capture the precise dimensions of an individual's auditory meatus. Subsequently, an electrode can be crafted with meticulous accuracy based on the acquired scanning data. Kappel et al.'s work has contributed to this area of research (Kappel et al., 2018). However, a prevailing technique involves 3D printing personalized earpieces that incorporate pin electrodes placed at specific positions. With the continuous advancement of 3D printing technologies,

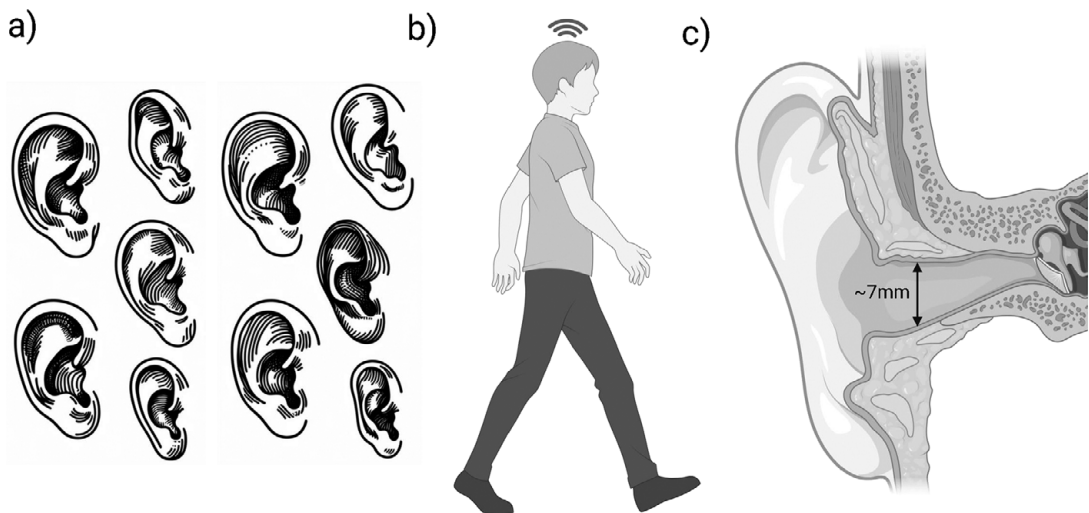


Figure 5. Three major challenges affecting hearable device performance and signal quality: (a) Variability in ear anatomy, differences in ear canal shape and size among users result in inconsistent performance. (b) Motion artifacts, as hearables are designed for daily wear, while movement during activities introduces noise, reducing signal quality. (c) Size constraints, the limited space within the ear canal, restrict the number and size of components that can be integrated into the device.

electrodes can be seamlessly integrated into the earpiece alongside all required electrical components, resulting in a highly personalized and optimized solution.

Another pioneering endeavor in this domain has been undertaken by Wang et al., who introduced a novel methodology centered around a spiral electrode (Z Wang et al., 2023). This electrode boasts a dual-layer design, encompassing SMPs containing an EAL and an EEGDL (Wang et al., 2023). The EEGDL comprises Au wires and insulating polyimide (PI) (Wang et al., 2023). A noteworthy feature of this electrode design is its capability to expand and spiral within the auditory meatus upon the application of heat (Wang et al., 2023). This innovative approach enables the electrode to seamlessly adapt to the unique curvature of the auditory meatus during the expansion process, resulting in a customized fit tailored to the individual's anatomical features. Kaveh et al.'s work contributed to this field by developing an ear-EEG electrode with an extendable plastic structure that effectively conforms its electrodes to the curvature of the ear (Kaveh et al., 2020).

The size of the ear canal can vary throughout different age groups. For example, for the age group 18–30 years, the right ear length is 60.65 ± 4.71 mm, while for the age group 51–64 years, the right ear length is 65.05 ± 3.57 mm (Japatti et al., 2018). Fourteen different ear shapes are being classified (Martinez et al., 2023). There are also gender differences being found where men's first bend upper, lower, anterior, and posterior lengths for both ears are longer than those for women (Yu et al., 2015). The separation of the human ear canal can be seen in Table 3.

Different approaches have been developed to address the difference in auditory. For example, 3D-printing technologies have been used to create personalized electrodes that ensure a proper fit, a concept that has long been applied in the hearing-aid field (Looney et al., 2011). Beyond individualized ear molds, mature solutions from the audiology and hearing-aid industries include the use of biocompatible silicone interfaces and soft polymer materials that can maintain comfort and reduce irritation during prolonged wear. Recent research prototypes have further explored dry and flexible electrodes, conductive coatings, and microstructured surfaces that improve skin contact without extensive preparation (Burgar, 2022). Looking ahead, future directions may involve self-adaptive ear interfaces, advanced impedance modeling for electrode design, and the translation of standardized manufacturing pipelines from hearing aids to hearables, which together could significantly improve signal fidelity and user acceptance.

3.2. Motion artifacts

Motion artifacts represent an ongoing challenge in the field of ear-EEG measurements. These artifacts, unwanted electrical signals induced by physical movements of the body or the measurement system, pose a significant issue for the accurate acquisition of EEG signals (Seok et al., 2021). Unlike scalp EEG, ear-EEG is less affected by eye blinking but more susceptible to motion artifacts originating from jaw and head movements, primarily due to the extended wire connections involved (Kappel et al., 2017). The magnitude of these motion artifacts is a particular concern, often exceeding that of the EEG signal by at least an order of magnitude (Seok et al., 2021). The consequences of these artifacts are far-reaching and include a reduced accuracy in automated signal sequence classification for clinical diagnostic purposes and disruptions in the smooth operation of BCI systems (Seok et al., 2021). Given the need for daily monitoring and real-world applications of hearable devices, effectively managing and mitigating motion

Table 3. Percentage distribution of human ear dimensions, including length of the ear canal and area ranges, based on anthropometric data (Martinez et al., 2023)

Length	%	Area	%
6–11	4.02	210–361	9.05
11–15	33.67	361–511	36.68
15–20	41.71	511–662	36.18
20–24	17.09	662–812	15.08
24–29	3.02	812–963	2.51

artifacts is crucial to ensure the reliability and clinical utility of ear-EEG measurements. Existing mitigation strategies, such as accelerometer-based noise filtering, have shown moderate success (Occhipinti et al., 2022), but they struggle to differentiate true neural signals from muscle activity. Novel approaches, such as adaptive filtering using independent component analysis and deep learning-based artifact removal, have demonstrated promise (Phadikar et al., 2020), but their real-time applicability in wearable devices remains an open question due to computational constraints.

A study introduced an innovative ear-EEG electrode design that employs memory foam as its base material (Goverdovsky et al., 2017). This choice of material effectively mitigates motion artifacts arising from both minor and substantial mechanical deformations of the ear canal walls (Goverdovsky et al., 2017). This electrode design also incorporates using two microphones to capture acoustic signals traversing through dense head tissues and uses these signals to cancel the motion artifacts in the EEG signal (Goverdovsky et al., 2017).

3.3. Design constraints and miniaturization challenges

The task of seamlessly integrating the complete analog front end and the MCU into a single earpiece to facilitate the wireless transmission of digital signals to a designated device remains a substantial challenge in this field. This challenge is further accentuated by the necessity of minimizing the distance between the electrode and the analog front end and the size of the auditory meatus (Mozaffari et al., 2021). One suggested approach entails the strategic distribution of electrical components around the external ear rather than direct insertion into the ear canal (Kaveh et al., 2020). However, even with this approach, the visibility of these components remains noticeable, potentially causing social discomfort. In practical scenarios, this situation might require the use of additional accessories, such as a hat, to effectively conceal the components.

It is important to acknowledge that while addressing this challenge entails inherent complexities, its resolution is attainable. The utilization of ASICs has emerged as a promising solution; however, it is fitting to recognize that producing a limited quantity of ASICs can involve significant costs. As time progresses, the continued advancement of manufacturing and electronics technologies contributes to the ongoing miniaturization of electronic components. This enduring trend plays a pivotal role in facilitating the seamless integration of all necessary components within the confined space of the earpiece.

4. Future directions

The future of hearables holds tremendous potential for advancements in both signal quality and overall system performance. Emerging technologies and innovative design strategies are poised to significantly enhance their accuracy, reliability, and user experience. As these advancements unfold, hearables will not only become more effective in capturing high-fidelity physiological signals but will also expand their role across a broader range of applications, integrating more deeply into healthcare, wellness, and everyday life. A conceptual overview of this future direction is illustrated in Figure 6.

4.1. Multi-sensor hearables

The integration of multiple sensors into hearable devices enables the simultaneous acquisition of diverse physiological signals, transforming these devices into powerful platforms for continuous health monitoring and medical diagnostics. This multi-sensor approach broadens the scope of measurable parameters, enhances data fusion capabilities, and improves signal quality through redundancy and noise mitigation techniques. By applying machine learning and advanced signal processing, multi-sensor hearables can derive more meaningful insights from complex physiological data, supporting both consumer wellness and clinical applications. Additionally, such sensor integration holds promise for other domains, including brain-machine interfaces (Martin et al., 2022; Bengler et al., 2023).

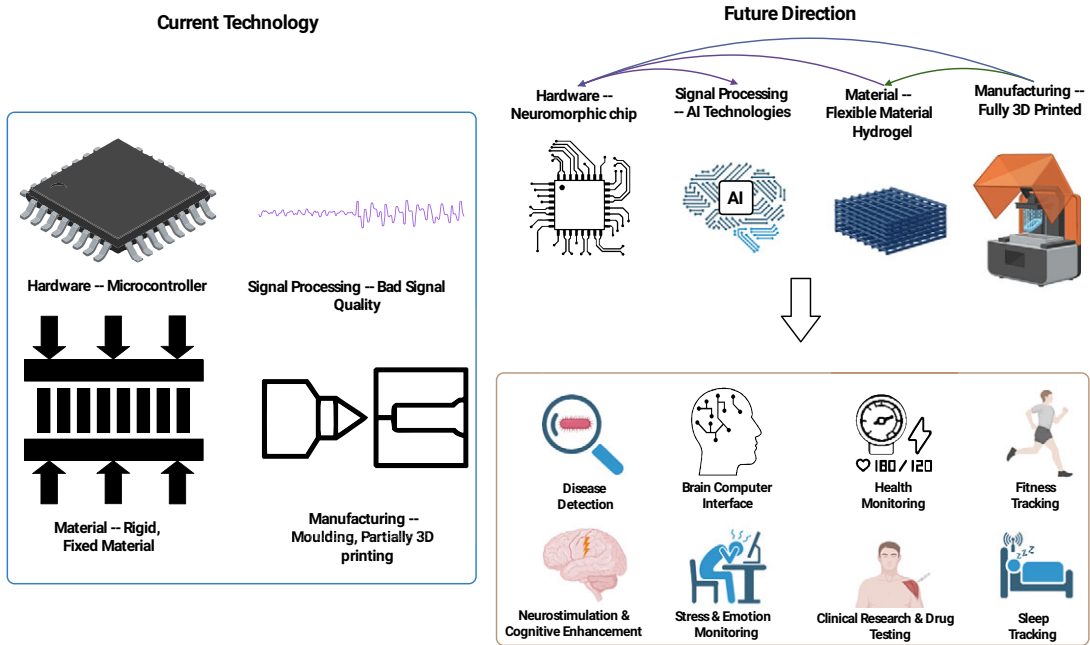


Figure 6. While current hearable technology often relies on microcontrollers and rigid-material electrodes produced through molding or partial 3D printing, leading to unstable signal quality, future advancements in both hardware and manufacturing techniques, such as the integration of neuromorphic chips with on-device AI and the use of flexible materials, promise more stable signal acquisition and real-time analysis. These innovations will greatly enhance and expand the applications of hearables across various domains.

Żyliński et al. introduced a hearable device capable of monitoring ECG, PPG, and heart sounds, providing comprehensive and multimodal heart rate monitoring (Żyliński et al., 2024). Similarly, Montanari et al. developed a hearable integrating kinetic, acoustic, optical, and thermal sensors, leveraging machine learning for advanced data analysis (Montanari et al., 2024). These innovations highlight the potential of hearables as versatile platforms for real-time health monitoring.

Such advancements demonstrate the potential of multi-sensor systems to transform hearables into powerful tools for continuous health tracking, with applications spanning general wellness to clinical diagnostics.

4.2. Advanced signal processing techniques

Hearables are becoming increasingly sophisticated, integrating advanced signal processing techniques to improve signal quality, enhance user experience, and expand their range of applications. Effective signal processing is crucial for extracting meaningful physiological data, ensuring reliable real-time monitoring, and enabling applications such as health tracking, cognitive assessments, and biometric authentication.

One of the key challenges in hearables is enhancing the SNR to ensure high-quality physiological data acquisition. Techniques such as filtering to remove noise and artifacts, segmentation to isolate relevant events, and feature extraction to identify critical signal patterns are commonly employed. These approaches are particularly useful in capturing bioelectrical signals like EEG, ECG, and PPG, as well as acoustic and temperature signals. Due to the compact nature of hearables, designing efficient AFE circuits remains a challenge. To address this, integrated circuit AFE designs have been explored to optimize signal acquisition while minimizing size and power consumption (Xu et al., 2017).

To overcome size and power constraints, several low-cost and efficient solutions have been developed. For instance, Teversham et al. designed a low-cost physiological monitoring system using an ESP32 MCU, integrating analog front-end components, such as a bandpass filter, differential amplifier, and notch filter (Teversham et al., 2022). This approach enables real-time signal decoding at a fraction of the cost of traditional medical devices, demonstrating the feasibility of low-cost, wearable physiological monitoring.

Utilizing external computational resources for additional signal processing offers another practical solution for enhancing portability and efficiency. Hölle and Bleichner introduced a system where a commercial amplifier and general-purpose hearable sensors were paired with a smartphone for real-time sound and biometric signal analysis (Hölle and Bleichner, 2023). By offloading computation to a smartphone, the hearable device itself can remain compact and energy-efficient while still benefiting from advanced signal processing capabilities.

Power efficiency is a critical factor for long-term hearable use. Lee et al. developed a low-power communication system utilizing body channel transmission, reducing power consumption and enabling continuous monitoring over extended periods (J Lee et al., 2019). This type of innovation is essential for daily health monitoring applications, such as heart rate tracking, respiratory monitoring, and stress detection.

Dedicated chips designed for hearables focus on optimizing high input impedance and low noise to effectively capture bioelectrical and acoustic signals in real-world environments. For example, Zheng et al. introduced a time-division multiplexing-based AFE with a capacitively coupled chopper design, achieving superior noise performance (Zheng, 2024). Similarly, Jin et al. developed a low-power AFE ASIC tailored for wearable applications, ensuring minimal power consumption while maintaining signal integrity (Jin et al., 2023).

These advancements in analog front-end design, power efficiency, and AI-driven processing are transforming hearables into powerful, multifunctional health monitoring tools. By addressing challenges related to cost, size, and signal processing, hearables are expanding their role in applications ranging from cardiovascular health monitoring and sleep tracking to cognitive enhancement and biometric security. It is important to note that Apple released a patent in the ear EEG domain, which enables the auto-selection of the best electrode for the current situation (Azemi et al., 2023).

4.3. Deployment of AI models

Advances in AI and edge computing hardware have significantly enhanced the feasibility of deploying AI models on wearable devices. These developments offer substantial benefits, including the delivery of actionable insights, early detection of health issues, and the prioritization of critical data for healthcare professionals. Furthermore, on-device training enables the creation of personalized models tailored to the unique physiological characteristics of individual users. However, due to the inherent constraints of hearables, such as limited computational resources and reduced input data channels, AI models must be carefully optimized for efficiency.

In the domain of EEG signal processing, several studies have demonstrated the promise of edge-optimized AI models. For example, Contreras et al. proposed an ultra-low-power seizure detection model specifically designed for integration into wearable systems, positioning it as a strong candidate for next-generation hearables (Herbozo Contreras et al., 2024). Similarly, Zhu et al. introduced a lightweight edge model for sleep staging based on single-channel EEG data, making it particularly suitable for wearable applications (Zhu et al., 2022). Complementing these approaches, Huang et al. developed a dedicated chip architecture for deploying AI models efficiently on edge devices (Huang et al., 2019).

The integration of AI significantly enhances the capabilities of hearables by improving signal interpretation, automation, and user interactivity. For instance, Mai et al. implemented a real-time emotion classification system using a 1D-Convolutional Neural Network on an embedded platform, utilizing fast Fourier transform and power spectral density features (Mai et al., 2023). AI-driven methods can also improve data quality by reducing noise and artifacts. Jayas et al. demonstrated an algorithm capable of

detecting motion and muscle artifacts in physiological signals, thereby enhancing the reliability of downstream analysis (Jayas et al., 2023).

Beyond signal enhancement, AI integration empowers hearables to deliver autonomous health insights in real time, often without requiring professional oversight. Neuromorphic computing, in particular, enables ultra-low-power, continuous on-device processing, which is ideal for long-term health monitoring (Sharifshazileh et al., 2021). Similarly, Field Programmable Gate Arrays (FPGAs) have been leveraged for energy-efficient AI inference. For example, Al-Ashmouny et al. showcased FPGA-based processing for sleep apnea detection using physiological data, underscoring the potential for real-time assessments in wearable applications (Al-Ashmouny et al., 2006).

For ECG signals, multiple efforts have aimed at achieving high performance within resource-constrained environments. Huang et al. developed an edge-friendly ECG classification model, while Huang et al. proposed a preprocessing-free model optimized for detecting heart abnormalities on low-power devices (Huang et al., 2024a; Huang et al., 2024b). Additionally, Huang et al. presented a novel framework for training large-scale models directly on edge platforms (Huang et al., 2025). In a practical demonstration, Meza-Rodriguez et al. successfully deployed a heart abnormality classification system on MCU, highlighting the viability of implementing sophisticated AI on compact hardware (Meza-Rodriguez et al., 2023).

Collectively, these efforts highlight the transformative potential of AI-enabled wearables. By supporting real-time analysis, personalization, and improved accessibility, AI-driven hearables are set to revolutionize both clinical and consumer health monitoring, positioning them as indispensable tools in modern healthcare.

4.4. Advanced material technologies

Advancements in material technologies have enabled the development of electrodes and components that enhance adaptability and comfort, allowing for a more personalized fit within the ear canal. These innovations improve both the functionality and wearability of in-ear biosignal monitoring systems, addressing challenges such as signal quality, durability, and long-term usability.

Ahn et al. introduced a technology utilizing 3D printing with silver ink to create stretchable electrodes that can be directly applied to the skin for biosignal monitoring (Ahn et al., 2009). Similarly, Kumar et al. developed a flexible supercapacitor capable of serving as a power source for wearable devices, while Xu et al. designed a stretchable battery that supports wireless charging, further enhancing the feasibility of fully flexible wearable systems (Xu et al., 2013; Kumar et al., 2016).

Hydrogel-based electrodes also offer unique advantages, particularly in the development of semi-dry electrodes. These materials can achieve low impedance between the electrode and the skin while maintaining durability and long-term stability. Ge et al. developed an EEG electrode incorporating hydrogels to achieve both low impedance and high longevity (Ge et al., 2023). However, the effectiveness of generalized ear-EEG electrodes may vary significantly due to the use of elastic materials. Since these electrodes rely on the tension of plastic components, variations in material elasticity can impact electrode-skin contact, potentially leading to inconsistencies in impedance and signal quality.

These advancements collectively pave the way for the development of fully flexible, high-performance in-ear biosignal monitoring systems. By improving comfort, durability, and energy efficiency, these materials enhance the practicality of hearables for long-term health monitoring and medical applications.

4.5. Advanced manufacturing technology

Recent advancements in manufacturing technology have significantly improved the efficiency and feasibility of producing complex, highly specialized hearable devices. Techniques such as 3D printing have revolutionized the production process, enabling precise customization to accommodate individual anatomical and functional requirements (Persad and Rocke, 2022).

For instance, 3D printing allows for the fabrication of personalized ear canal components, enhancing both comfort and signal quality by ensuring an optimal fit (Kaveh et al., 2020). Additionally, advanced material technologies, such as biocompatible polymers and conductive inks, facilitate the seamless integration of sensors and electronic components directly into the device structure. This integration reduces assembly complexity, improves signal fidelity, and enhances device durability.

Furthermore, miniaturization techniques have enabled the development of compact, low-profile hearables capable of housing multifunctional sensors, wireless communication modules, and energy-efficient processing units. These innovations help address challenges related to anatomical variability, device miniaturization, and long-term wearability, paving the way for the next generation of customized, high-performance hearable devices.

4.6. Brain–computer interface

As portable devices for detecting EEG signals, hearables have the potential to significantly advance BCI technology by providing a discreet, wearable alternative to traditional EEG systems. BCIs enable direct communication between the brain and external devices, with applications ranging from neuroprosthetic control and cognitive monitoring to assistive communication for individuals with paralysis.

Current BCI systems typically rely on either invasive electrodes, such as electrocorticography implants, or noninvasive scalp EEG systems that use wet electrodes and multichannel headsets (Miller et al., 2020; Hsieh et al., 2024). Although scalp EEG provides higher spatial resolution than ear-EEG, its bulky setup, dependence on gel-based electrodes, and susceptibility to motion artifacts greatly limit its practicality outside controlled laboratory settings (Asayesh et al., 2025). In contrast, ear-EEG offers a more portable and user-friendly alternative, and has been increasingly recognized as a promising solution for assisting individuals with disabilities in controlling prosthetic devices (Maibam et al., 2024; Liu et al., 2025).

With the development of high-quality ear-EEG recording, hearables could address these limitations by offering:

1. A more user-friendly, noninvasive interface for BCI applications.
2. Continuous brain monitoring in real-world environments.
3. Improved social acceptability, as they resemble common earbuds rather than medical devices.

However, in order to achieve the use of BCI, there are still some specific challenges that remain to be solved:

1. Low spatial resolution: Ear-EEG captures fewer electrodes and less choice in positions than traditional scalp EEG, limiting the amount of brain activity that can be recorded with high signal quality (Looney et al., 2014). As a result, certain neural signals may not be detected, reducing the effectiveness of BCIs. Future advancements may include the development of multi-electrode arrays or signal reconstruction techniques to enhance spatial resolution and improve overall performance.
2. Processing constraints: BCI applications require low-latency signal processing to enable real-time interactions. However, the computational capacity of hearables is constrained by size, thermal limits, and power efficiency (Haider and Guragain, 2023). Lightweight edge-computing architectures, neuromorphic processors, or dedicated BCI hardware accelerators could provide solutions to enhance real-time processing capabilities without excessive power consumption.
3. Wireless data transmission: Real-time BCI applications demand high-bandwidth, low-latency data transfer, which is challenging given the current wireless communication standards available in hearables. Bluetooth low energy offers power efficiency but is limited in data throughput, while body channel communication presents an emerging alternative with the potential to reduce interference and improve transmission reliability (Debener et al., 2016). Future work should focus

on hybrid communication methods that optimize between latency, power consumption, and bandwidth availability.

4. **Power constraints:** The computational demands of real-time EEG processing, multichannel high sampling rate acquisition, and continuous wireless transmission significantly increase power consumption, posing a major challenge for portable BCIs (Edelman et al., 2024). Current battery technology is insufficient for long-duration operation without frequent recharging. Advancements in energy-efficient circuits, ultra-low-power AI models, and energy harvesting technologies (e.g., thermoelectric or piezoelectric power generation) are needed to enhance the viability of long-term, real-world use.

5. Conclusion

This article has reviewed current hearable technologies and evaluated the performance of various ear-EEG electrode implementations, including both generalized and personalized designs. A comprehensive comparison was conducted across systems based on sensing modality, electrode count, impedance characteristics, sampling rates, and electrode materials.

Hearables have emerged as a powerful and unobtrusive platform for EEG monitoring, enabling continuous tracking of brain activity in real-world environments. By leveraging in-ear EEG sensing, they offer a user-friendly, discreet, and portable alternative to conventional scalp EEG systems. Demonstrated applications include sleep staging, cognitive state monitoring, emotion recognition, and neurological diagnostics. Their anatomical proximity to the temporal cortex makes them particularly effective for capturing brain rhythms related to auditory and cognitive processing.

Although ear-EEG recordings can achieve SNR comparable to scalp EEG for activity originating from temporal brain regions, performance typically degrades for signals from other cortical areas due to spatial constraints and signal attenuation. This limits their suitability for applications requiring broad spatial coverage or high-resolution mapping of neural activity.

Nevertheless, current hearable devices are capable of capturing clinically and functionally meaningful EEG signals. With ongoing advancements in materials science, fabrication techniques, miniaturized electronics, and advanced signal processing, future hearables are expected to support more complex applications, such as BCIs, mental health monitoring, and fitness tracking, bringing us closer to practical, widely accessible mobile neurotechnology.

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References

- Ahn BY, Duoss EB, Motala MJ, Guo X, Park SI, Xiong Y, Yoon J, Nuzzo RG, Rogers JA and Lewis JA (2009) Omnidirectional printing of flexible, stretchable, and spanning silver microelectrodes. *Science* **323**(5921), 1590–1593.
- Al-Ashmouny KM, Hamed HM and Morsy AA (2006) FPGA-based sleep apnea screening device for home monitoring. In *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, pp. 5948–5951.

- Asayesh A, Warsito IF, Hauelsen J, Fiedler P and Vanhatalo S (2025) Neonatal electroencephalogram recording with a dry electrode cap: a feasibility study. *Sensors (Basel, Switzerland)* **25**(3), 966.
- Azemi E, Moin A, Pragada A, Lu JHC, Powell VM, Minxha J and Hotelling SP (2023) Biosignal sensing device using dynamic selection of electrodes. US Patent App. 18/094,841.
- Azhar A, Gillani SW, Mohiuddin G and Majeed RA (2020) A systematic review on clinical implication of continuous glucose monitoring in diabetes management. *Journal of Pharmacy and Bioallied Sciences* **12**(2), 102–111.
- Bech Christensen C, Hietkamp RK, Harte JM, Lunner T and Kidmose P (2018) Toward EEG-assisted hearing aids: objective threshold estimation based on ear-EEG in subjects with sensorineural hearing loss. *Trends in Hearing* **22**, 2331216518816203.
- Bengler K, Harbauer CM and Fleischer M (2023) Exoskeletons: a challenge for development. *Wearable Technologies* **4**, e1. <https://doi.org/10.1017/wtc.2023.1>.
- Bjarke Mikkelsen K, Rezaei Tabar Y, Rævsbæk Birch L, Lind Kappel S, Bech Christensen C, Dalskov Mosgaard L, Otto M, Christian Hemmsen M, Lind Rank M and Kidmose P (2025) Ear-EEG sleep monitoring data sets. *Scientific Data* **12**(1), 301.
- Bleichner MG, Lundbeck M, Selisky M, Minow F, Jäger M, Emkes R, Debener S and De Vos M (2015) Exploring miniaturized EEG electrodes for brain-computer interfaces. An EEG you do not see? *Physiological Reports* **3**(4), e12362.
- Bleichner MG, Mirkovic B and Debener S (2016) Identifying auditory attention with ear-EEG: cEEGrid versus high-density cap-EEG comparison. *Journal of Neural Engineering* **13**(6), 066004.
- Borup K, Kidmose P, Phan H and Mikkelsen K (2023) Automatic sleep scoring using patient-specific ensemble models and knowledge distillation for ear-EEG data. *Biomedical Signal Processing and Control* **81**, 104496.
- Bouzid Z, Al-Zaiti SS, Bond R and Sejdíć E (2022) Remote and wearable ECG devices with diagnostic abilities in adults: a state-of-the-science scoping review. *Heart Rhythm* **19**(7), 1192–1201.
- Brieger D, Amerena J, Attia J, Bajorek B, Chan KH, Connell C, Freedman B, Ferguson C, Hall T, Haqqani H, et al. (2018) National Heart Foundation of Australia and cardiac Society of Australia and New Zealand: Australian clinical guidelines for the diagnosis and management of atrial fibrillation 2018. *Medical Journal of Australia* **209**(8), 356–362.
- Budidha K and Kyriacou P (2018) In vivo investigation of ear canal pulse oximetry during hypothermia. *Journal of Clinical Monitoring and Computing* **32**(1), 97–107.
- Burgar P (2022) Design of flexible dry CNT/PDMS electrodes for in-ear EEG. Master's Thesis, Delft University of Technology.
- Byrne S (2014) *Survey results: Devices we use daily in 2014*. <https://www.cnet.com/culture/survey-results-devices-we-usedaily-in-2014/> (accessed 02 August 2023).
- Castaneda D, Esparza A, Ghamari M, Soltanpur C and Nazeran H (2018) A review on wearable photoplethysmography sensors and their potential future applications in health care. *International Journal of Biosensors & Bioelectronics* **4**(4), 195.
- Choi J, Kaongoen N, Choi H, Kim M, Kim BH and Jo S (2023) Decoding auditory-evoked response in affective states using wearable around-ear EEG system. *Biomedical Physics & Engineering Express* **9**(5), 055029.
- Clarke M, Gokalp H, Fursse J and Jones RW (2015) Dynamic threshold analysis of daily oxygen saturation for improved management of COPD patients. *IEEE Journal of Biomedical and Health Informatics* **20**(5), 1352–1360.
- Davies HJ, Williams I, Peters NS and Mandic DP (2020) In-ear SpO₂: a tool for wearable, unobtrusive monitoring of core blood oxygen saturation. *Sensors* **20**(17), 4879.
- Debener S, Kranczioch C and De Vos M (2016) Electroencephalography: current trends and future directions. *Neuroeconomics* **359–373**. https://link.springer.com/chapter/10.1007/978-3-642-35923-1_19.
- Edelman BJ, Zhang S, Schalk G, Brunner P, Müller-Putz G, Guan C and He B (2024) Non-invasive brain-computer interfaces: state of the art and trends. *IEEE Reviews in Biomedical Engineering* **18**, 26–49.
- Eickenscheidt M, Schäfer P, Baslan Y, Schwarz C and Stieglitz T (2020) Highly porous platinum electrodes for dry ear-EEG measurements. *Sensors* **20**(11), 3176.
- Evenson KR, Goto MM and Furberg RD (2015) Systematic review of the validity and reliability of consumer-wearable activity trackers. *International Journal of Behavioral Nutrition and Physical Activity* **12**, 1–22.
- Ferlini A, Montanari A, Min C, Li H, Sassi U and Kawsar F (2021) In-ear PPG for vital signs. *IEEE Pervasive Computing* **21**(1), 65–74.
- Ge X, Guo Y, Gong C, Han R, Feng J, Ji J, Sun Z, Gao J, Bian F and Xu Z (2023) High-conductivity, low-impedance, and high-biological-adaptability ionic conductive hydrogels for ear-EEG acquisition. *ACS Applied Polymer Materials* **5**(10), 8151–8158.
- Goldberger AL and Goldberger E (1981) Clinical electrocardiography, a simplified approach. *Critical Care Medicine* **9**(12), 891–892.
- Gomes N, Pato M, Lourenco AR and Datia N (2023) A survey on wearable sensors for mental health monitoring. *Sensors* **23**(3), 1330.
- Goverdovsky V, Rosenberg W v, Nakamura T, Looney D, Sharp DJ, Papavassiliou C, Morrell MJ and Mandic DP (2017) Hearables: multimodal physiological in-ear sensing. *Scientific Reports* **7**(1), 6948.
- Hafen BB and Sharma S (2018) *Oxygen saturation*. StatPearls.
- Haider A and Guragain B (2023) Challenges and future trends of EEG as a frontier of clinical applications. In *2023 IEEE International Conference on Electro Information Technology (eIT)*. IEEE, pp. 484–498.
- Hammour G, Davies H, Atzori G, Della Monica C, Ravindran KK, Revell V, Dijk DJ and Mandic DP (2024) From scalp to ear-EEG: a generalisable transfer learning model for automatic sleep scoring in older people. *IEEE Journal of Translational Engineering in Health and Medicine* **12**, 448–456.

- Hammour G, Yarici M, Rosenberg W von and Mandic DP** (2019) Hearables: feasibility and validation of in-ear electrocardiogram. In *41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 5777–5780.
- Henry JC** (2006) Electroencephalography: basic principles, clinical applications, and related fields. *Neurology* **67**(11), 2092–2092.
- Herbozo Contreras LF, Huang Z, Yu L, Nikpour A and Kavehei O** (2024) Biological plausible algorithm for seizure detection: toward AI-enabled electroceuticals at the edge. *APL Machine Learning* **2**(2).
- Hölle D and Bleichner MG** (2023) Smartphone-based ear-electroencephalography to study sound processing in everyday life. *European Journal of Neuroscience* **58**(7), 3671–3685.
- Holtze B, Rosenkranz M, Jaeger M, Debener S and Mirkovic B** (2022) Ear-EEG measures of auditory attention to continuous speech. *Frontiers in Neuroscience* **16**, 869426.
- Hsieh JC, Alawieh H, JdR M and Wang H** (2024) The evolving landscape of non-invasive EEG-brain-computer interfaces: current trends and future perspectives. *Device* **2**(12), 1–3.
- Huang Z, Herbozo Contreras LF, Leung WH, Yu L, Truong ND, Nikpour A and Kavehei O** (2024a) Efficient edge-AI models for robust ECG abnormality detection on resource-constrained hardware. *Journal of Cardiovascular Translational Research* **17**(4), 879–892.
- Huang Z, Herbozo Contreras LF, Yu L, Truong ND, Nikpour A and Kavehei O** (2024b) S4D-ECG: a shallow state-of-the-art model for cardiac abnormality classification. *Cardiovascular Engineering and Technology* **15**(3), 305–316.
- Huang M, Tamura T, Yoshimura T, Tsuchikawa T and Kanaya S** (2016) Wearable deep body thermometers and their uses in continuous monitoring for daily healthcare. In *38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 177–180.
- Huang YD, Wang KY, Ho YL, He CY and Fang WC** (2019) An edge AI system-on-chip design with customized convolutional-neural-network architecture for real-time EEG-based affective computing system. In *2019 IEEE Biomedical Circuits and Systems Conference (BioCAS)*. IEEE, pp. 1–4.
- Huang Z, Yu L, Contreras LFH, Eshraghian K, Truong ND, Nikpour A and Kavehei O** (2025) Advancing privacy-aware machine learning on sensitive data via edge-based continual μ -training for personalized large models. *Machine Learning: Science and Technology* **6**(1), 015025.
- Hunn N** (2014) *Hearables – The New Wearables*. <https://wt-obk.wearable-technologies.com/2014/04/hearables-the-new-wearables/> (accessed 13 March 2025).
- Japatti SR, Engineer PJ, Reddy BM, Tiwari AU, Siddegowda CY and Hammannavar RB** (2018) Anthropometric assessment of the normal adult human ear. *Annals of Maxillofacial Surgery* **8**(1), 42–50.
- Jayas T, Adarsh A, Muralidharan K, Gubbi J, Pal A et al** (2023) Computer aided detection of dominant artifacts in ear-EEG signal. In *2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, pp. 4423–4428.
- Jeong DH and Jeong J** (2020) In-ear EEG based attention state classification using echo state network. *Brain Sciences* **10**(6), 321.
- Jin H, Hu W, Zhao Y, Jiang Y, Ye Y, Wang S and Qin Y** (2023) A 1.5 mm 2 4-channel EEG/BIOZ acquisition ASIC with 15.2-bit 3-step ADC based on a signal-dependent low-power strategy. *IEEE Transactions on Biomedical Circuits and Systems* **17**, 1111–1124.
- Joyner M, Hsu SH, Martin S, Dwyer J, Chen DF, Sameni R, Waters SH, Borodin K, Clifford GD, Levey AI, Hixson J, Winkel D and Berent J** (2024) Using a standalone ear-EEG device for focal-onset seizure detection. *Bioelectronic Medicine* **10**(1), 4.
- Juez J, Henao D, Segura F, Gómez R, Le Van Quyen M and Valderrama M** (2021) Development of a wearable system with in-ear EEG electrodes for the monitoring of brain activities: an application to epilepsy. In *2nd IEEE International Congress of Biomedical Engineering and Bioengineering (CI-IB&BI)*, IEEE, pp. 1–4.
- Kaniusas E** (2011) Fundamentals of biosignals. In *Biomedical Signals and Sensors I: Linking Physiological Phenomena and Biosignals*, Springer, pp. 1–26.
- Kappel SL and Kidmose P** (2017) High-density ear-EEG. In *39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 2394–2397.
- Kappel SL, Looney D, Mandic DP and Kidmose P** (2017) Physiological artifacts in scalp EEG and ear-EEG. *Biomedical Engineering Online* **16**(1), 1–16.
- Kappel SL, Rank ML, Toft HO, Andersen M and Kidmose P** (2018) Dry-contact electrode ear-EEG. *IEEE Transactions on Biomedical Engineering* **66**(1), 150–158.
- Kaveh R, Doong J, Zhou A, Schwendeman C, Gopalan K, Burghardt FL, Arias AC, Maharbiz MM and Muller R** (2020) Wireless user-generic ear EEG. *IEEE Transactions on Biomedical Circuits and Systems* **14**(4), 727–737.
- Kaveh R, Schwendeman C, Pu L, Arias AC and Muller R** (2024) Wireless ear EEG to monitor drowsiness. *Nature Communications* **15**(1), 6520.
- Kidmose P, Looney D, Jochumsen L and Mandic DP** (2013) Ear-EEG from generic earpieces: a feasibility study. In *35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 543–546.
- Klaren C v, Majj A, Marsman L and Drongelen A v** (2024) The evaluation of cEEGrids for fatigue detection in aviation. *SLEEP Advances* **5**(1), zpa009.
- Kumar P, Di Mauro E, Zhang S, Pezzella A, Soavi F, Santato C and Ciccoira F** (2016) Melanin-based flexible supercapacitors. *Journal of Materials Chemistry C* **4**(40), 9516–9525.

- Lee XK, Chee NI, Ong JL, Teo TB, van RE, Lo JC and Chee MW (2019) Validation of a consumer sleep wearable device with actigraphy and polysomnography in adolescents across sleep opportunity manipulations. *Journal of Clinical Sleep Medicine* 15(9), 1337–1346.
- Lee J, Lee KR, Ha U, Kim JH, Lee K, Gweon S, Jang J and Yoo HJ (2019) A0.8-V82.9- μ W in-ear BCI controller IC with 8.8 PEF EEG instrumentation amplifier and wireless BAN transceiver. *IEEE Journal of Solid-State Circuits* 54(4), 1185–1195.
- Levander MS and Grodzinsky E (2017) Variation in normal ear temperature. *The American Journal of the Medical Sciences* 354(4), 370–378.
- Liang H, Wang Y, Li H, Wang Y, Liu PX and Liu R (2023) Development and characterization of a dry ear-EEG sensor with a generic flexible earpiece. *IEEE Transactions on Instrumentation and Measurement* 72, 1–12.
- Liu XY, Wang WL, Liu M, Chen MY, Pereira T, Doda DY, Ke YF, Wang SY, Wen D, Tong XG et al (2025) Recent applications of EEG-based brain-computer-interface in the medical field. *Military Medical Research* 12(1), 14.
- Logar C, Walzl B and Lechner H (2008) Role of long-term EEG monitoring in diagnosis and treatment of epilepsy. *European Neurology* 34(Suppl. 1), 29–32. <https://doi.org/10.1159/000119506>.
- Looney D, Kidmose P and Mandic DP (2014) Ear-EEG: user-centered and wearable BCI. In *Brain-Computer Interface Research: A State-of-the-Art Summary-2*, pp. 41–50.
- Looney D, Kidmose P, Park C, Ungstrup M, Rank ML, Rosenkranz K and Mandic DP (2012) The in-the-ear recording concept: user-centered and wearable brain monitoring. *IEEE Pulse* 3(6), 32–42.
- Looney D, Park C, Kidmose P, Rank ML, Ungstrup M, Rosenkranz K and Mandic DP (2011) An in-the-ear platform for recording electroencephalogram. In *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, pp. 6882–6885.
- López-Campos JL, Tan W and Soriano JB (2016) Global burden of COPD. *Respirology* 21(1), 14–23.
- Mai ND, Nguyen HT and Chung WY (2023) Real-time on-Chip machine-learning-based wearable behind-the-ear electroencephalogram device for emotion recognition. *IEEE Access* 11, 47258–47271.
- Maibam PC, Pei D, Olikkal P, Vinjamuri RK and Kakoty NM (2024) Enhancing prosthetic hand control: a synergistic multi-channel electroencephalogram. *Wearable Technologies* 5, e18.
- Martin WB, Boehler A, Hollander KW, Kinney D, Hitt JK, Kudva J and Sugar TG (2022) Development and testing of the aerial porter exoskeleton. *Wearable Technologies* 3, e1.
- Martinez J, Hwee GZ, Yap L, De Chua KW, Kamath S, Chung CKR, Teo WYB, Tan CKL, Dritsas S and Simpson RE (2023) Lexicon for classifying ear-canal shapes. *Scientific Reports* 13(1), 11866.
- Masè M, Micarelli A and Strapazzon G (2020) Hearables: new perspectives and pitfalls of in-ear devices for physiological monitoring. A scoping review. *Frontiers in Physiology* 11, 568886.
- Matsumoto K, Temiz Y, Taghavi H, Cornelius EL, Mori H and Michel B (2019) An earbud-type wearable (a hearable) with vital parameter sensors for early detection and prevention of heat-stroke. In *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 7049–7055.
- Meek S and Morris F (2002) ABC of clinical electrocardiography: introduction. I—Leads, rate, rhythm, and cardiac axis. *BMJ: British Medical Journal* 324(7334), 415.
- Mendelson Y and Pujary C (2003) Measurement site and photodetector size considerations in optimizing power consumption of a wearable reflectance pulse oximeter. In *25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC, IEEE Cat. No. 03CH37439)*. vol 4. IEEE, pp. 3016–3019.
- Meza-Rodriguez M, De La Cruz L and Cáceres-DelAguila JA (2023) Development of an electrocardiographic signal classifier for bundle branch blocks, applying tiny machine learning. In *2023 IEEE XXX International Conference on Electronics, Electrical Engineering and Computing (INTERCON)*. IEEE, pp. 1–6.
- Mikkelsen KB, Kappel SL, Mandic DP and Kidmose P (2015) EEG recorded from the ear: characterizing the ear-EEG method. *Frontiers in Neuroscience* 9, 438.
- Mikkelsen KB, Kidmose P and Rezaei Tabar Y (2019) *Ear-EEG Sleep Monitoring 2019 (EESM19)-OpenNeuro*. OpenNeuro dataset
- Mikkelsen KB, Villadsen DB, Otto M and Kidmose P (2017) Automatic sleep staging using ear-EEG. *Biomedical Engineering Online* 16(1), 1–15.
- Miller KJ, Hermes D and Staff NP (2020) The current state of electrocorticography-based brain–computer interfaces. *Neurosurgical Focus* 49(1), E2.
- Montanari A, Thangarajan A, Al-Naimi K, Ferlini A, Liu Y, Balaji AN and Kawsar F (2024) OmniBuds: a sensory earable platform for advanced bio-sensing and on-device machine learning. *arXiv preprint arXiv:2410.04775*.
- Moumane H, Pazuelo J, Nassar M, Juez JY, Valderrama M and Le Van Quyen M (2024) Signal quality evaluation of an in-ear EEG device in comparison to a conventional cap system. *Frontiers in Neuroscience* 18, 1441897.
- Mozaffari M, Nash R and Tucker AS (2021) Anatomy and development of the mammalian external auditory canal: implications for understanding canal disease and deformity. *Frontiers in Cell and Developmental Biology* 8, 617354.
- Nakamura T, Alqurashi YD, Morrell MJ and Mandic DP (2019) Hearables: automatic overnight sleep monitoring with standardized in-ear EEG sensor. *IEEE Transactions on Biomedical Engineering* 67(1), 203–212.
- Ne CKH, Muzaffar J, Amlani A and Bance M (2021) Hearables, in-ear sensing devices for bio-signal acquisition: a narrative review. *Expert Review of Medical Devices* 18(sup1), 95–128.

- Occchipinti E, Davies HJ, Hammour G and Mandic DP** (2022) Hearables: artefact removal in ear-EEG for continuous 24/7 monitoring. In *2022 International Joint Conference on Neural Networks (IJCNN)*. IEEE, pp. 1–6.
- Olson KD, O'Brien P, Lin AS, Fabry DA, Hanke S and Schroeder MJ** (2023) A continuously worn dual temperature sensor system for accurate monitoring of Core body temperature from the ear canal. *Sensors* **23**(17), 7323.
- Pedrana A, Comotti D, Re V and Traversi G** (2020) Development of a wearable in-ear PPG system for continuous monitoring. *IEEE Sensors Journal* **20**(23), 14482–14490.
- Perez MV, Mahaffey KW, Hedlin H, Rumsfeld JS, Garcia A, Ferris T, Balasubramanian V, Russo AM, Rajmane A, Cheung L, Hung G, Lee J, Kowey P, Talati N, Nag D, Gummidipundi SE, Beatty A, Hills MT, Desai S, Granger CB, Desai M, Turakhia MP and Apple Heart Study Investigators** (2019) Large-scale assessment of a smartwatch to identify atrial fibrillation. *New England Journal of Medicine* **381**(20), 1909–1917.
- Persad J and Rocke S** (2022) A survey of 3D printing technologies as applied to printed electronics. *IEEE Access* **10**, 27289–27319.
- Phadikar S, Sinha N and Ghosh R** (2020) Automatic EEG eyeblink artefact identification and removal technique using independent component analysis in combination with support vector machines and denoising autoencoder. *IET Signal Processing* **14**(6), 396–405.
- Plazak J and Kersten-Oertel M** (2018) A survey on the affordances of “Hearables”. *Inventions* **3**(3), 48.
- Rosenow F and Lüders H** (2001) Presurgical evaluation of epilepsy. *Brain* **124**(9), 1683–1700.
- Semmlow J** (2018) Chapter 1 – The big picture: bioengineering signals and systems. In Semmlow J (ed), *Circuits, Signals and Systems for Bioengineers*, 3rd Edn. Biomedical Engineering. Academic Press, pp. 3–50. <https://doi.org/10.1016/B978-0-12-809395-5.00001-1>.
- Seok D, Lee S, Kim M, Cho J and Kim C** (2021) Motion artifact removal techniques for wearable EEG and PPG sensor systems. *Frontiers in Electronics* **2**, 685513.
- Sergeeva A, Christensen CB and Kidmose P** (2024) Effect of stimulus bandwidth on the auditory steady-state response in scalp- and ear-EEG. *Ear and Hearing* **45**(3), 626–635.
- Sharifshazileh M, Burelo K, Sarnthein J and Indiveri G** (2021) An electronic neuromorphic system for real-time detection of high frequency oscillations (HFO) in intracranial EEG. *Nature Communications* **12**(1), 3095.
- Sintotskiy G and Hinrichs H** (2020) In-ear-EEG—a portable platform for home monitoring. *Journal of Medical Engineering & Technology* **44**(1), 26–37.
- Smital L, Haider CR, Vitek M, Leinveber P, Jurak P, Nemcova A, Smisek R, Marsanova L, Provaznik I, Felton CL, Gilbert BK and Holmes DR** (2020) Real-time quality assessment of long-term ECG signals recorded by wearables in free-living conditions. *IEEE Transactions on Biomedical Engineering* **67**(10), 2721–2734.
- Soon S, Svavarsdottir H, Downey C and Jayne DG** (2020) Wearable devices for remote vital signs monitoring in the outpatient setting: an overview of the field. *BMJ Innovations* **6**(2), 55–71.
- Streckfus CF** (2022) Exocrine Glands of the Sensory Organs. In *Exocrinology: A Textbook and Atlas of the Exocrine Cells, Glands and Organs*. Cham: Springer International Publishing, pp. 109–118. https://doi.org/10.1007/978-3-030-97552-4_9.
- Tabar YR, Mikkelsen KB, Rank ML, Hemmsen MC, Otto M and Kidmose P** (2021) Ear-EEG for sleep assessment: a comparison with actigraphy and PSG. *Sleep and Breathing* **25**, 1693–1705.
- Tabar YR, Mikkelsen KB, Shenton N, Kappel SL, Bertelsen AR, Nikbakht R, Toft HO, Henriksen CH, Hemmsen MC, Rank ML, Otto M and Kidmose P** (2023) At-home sleep monitoring using generic ear-EEG. *Frontiers in Neuroscience* **17**, 987578.
- Tatum IVVO** (2001) Long-term EEG monitoring: a clinical approach to electrophysiology. *Journal of Clinical Neurophysiology* **18**(5), 442–455.
- Teversham J, Wong SS, Hsieh B, Rapeaux A, Troiani F, Savolainen O, Zhang Z, Maslik M and Constantinou TG** (2022) Development of an ultra low-cost SSVEP-based BCI device for real-time on-device decoding. In *2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, pp. 208–213.
- Vitaterna MH, Takahashi JS and Turek FW** (2001) Overview of circadian rhythms. *Alcohol Research & Health* **25**(2), 85.
- Von Rosenberg W, Chanwimalueang T, Goverdovsky V, Peters NS, Papavassiliou C and Mandic DP** (2017) Hearables: feasibility of recording cardiac rhythms from head and in-ear locations. *Royal Society Open Science* **4**(11), 171214.
- Wang Z, Shi N, Zhang Y, Zheng N, Li H, Jiao Y, Cheng J, Wang Y, Zhang X, Chen Y, Chen Y, Wang H, Xie T, Wang Y, Ma Y, Gao X and Feng X** (2023) Conformal in-ear bioelectronics for visual and auditory brain-computer interfaces. *Nature Communications* **14**(1), 4213.
- Xu Y, De la Paz E, Paul A, Mahato K, Sempionatto JR, Tostado N, Lee M, Hota G, Lin M, Uppal A, et al.** (2023) In-ear integrated sensor array for the continuous monitoring of brain activity and of lactate in sweat. *Nature Biomedical Engineering* **7**(10), 1307–1320.
- Xu J, Mitra S, Van Hoof C, Yazicioglu RF and Makinwa KA** (2017) Active electrodes for wearable EEG acquisition: review and electronics design methodology. *IEEE Reviews in Biomedical Engineering* **10**, 187–198.
- Xu S, Zhang Y, Cho J, Lee J, Huang X, Jia L, Fan JA, Su Y, Su J, Zhang H, Cheng H, Lu B, Yu C, Chuang C, Kim TI, Song T, Shigetani K, Kang S, Dagdeviren C, Petrov I, Braun PV, Huang Y, Paik U and Rogers JA** (2013) Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems. *Nature Communications* **4**(1), 1543.
- Yarici MC, Amadori P, Davies H, Nakamura T, Lingg N, Demiris Y and Mandic DP** (2023) Hearables: ear EEG based driver fatigue detection. *arXiv preprint: 2301.06406*.

- Yetisen AK, Martínez-Hurtado JL, Ünal B, Khademhosseini A and Butt H** (2018) Wearables in medicine. *Advanced Materials* **30**(33), 1706910.
- Yu JF, Lee KC, Wang RH, Chen YS, Fan CC, Peng YC, Tu TH, Chen CI and Lin KY** (2015) Anthropometry of external auditory canal by non-contactable measurement. *Applied Ergonomics* **50**, 50–55.
- Yu L, Xu Z, Contreras LH and Kavehei O** (2024) An additively manufactured 3D printed electronics system for personalized ear-EEG. In *2024 International Conference on Electrical, Computer and Energy Technologies (ICECET)*. IEEE, pp. 1–6.
- Zhang Q, Zeng X, Hu W and Zhou D** (2017) A machine learning-empowered system for long-term motion-tolerant wearable monitoring of blood pressure and heart rate with ear-ECG/PPG. *IEEE Access* **5**, 10547–10561.
- Zheng H** (2024) A TDM-based analog front-end for ear-EEG recording with 83-G Ω input impedance, 384-mV DC tolerance and 0.47- μ Vrms input-referred noise. *arXiv preprint arXiv:2402.17538*.
- Zhou A, Zhang L, Yuan X and Li C** (2023) A signal prediction-based method for motor imagery EEG classification. *Biomedical Signal Processing and Control* **86**, 105139.
- Zhu L, Wang C, He Z and Zhang Y** (2022) A lightweight automatic sleep staging method for children using single-channel EEG based on edge artificial intelligence. *World Wide Web* **25**(5), 1883–1903.
- Żyliński M, Nassibi A, Occhipinti E, Malik A, Bermond M, Davies HJ and Mandic DP** (2024) Hearables: in-ear multimodal data fusion for robust heart rate estimation. *BioMedInformatics* **4**(2), 911–920.