Audio-Centric Earable Computing: Connecting the Device, the Body, and the User

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Abstract

Future personal computing systems should understand users, adapt to their states, and support seamless everyday interaction. Earables are well-suited for this vision due to their long-term wearability, stable head-centered placement, and proximity to physiological sources. Audio, as the most native and universal channel on earables, can serve as a unifying foundation for integrated computing. Through three systems spanning playback enhancement, physiological sensing, and passive authentication, we show how audio connects the device, the body, and the user. This suggests a broader role for earables as human-centered computing interfaces.

CCS Concepts

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

Keywords

Earables, Breathing Monitoring, Authentication

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1 Introduction

Future personal computing systems should not only provide functionality, but also continuously understand users, adapt to their states, and enable seamless interaction in everyday life. Realizing this vision requires a platform that can be worn for long periods, imposes minimal burden, and natively supports both input and output. Existing solutions often rely on task-specific designs, fragmented sensing pipelines, or additional hardware, limiting their scalability and practicality. In this context, earable devices have emerged as a promising platform. Originally designed for audio playback and communication, earables are now evolving into general-purpose personal computing devices [5]. Their stable placement around the head, long-wearing, and proximity to both the user and surrounding acoustic environment make them well-suited for continuous, low-burden, human-centered computing.

Despite this potential, current earable systems remain fragmented across functions. Audio playback quality varies significantly across devices, with low-end earphones often providing poor listening experiences. Earables are also naturally positioned to capture physiological signals such as breathing, yet existing approaches often focus only on coarse metrics like breathing rate. Meanwhile, authentication methods for privacy-sensitive applications are often intrusive, sensitive to noise and motion, or computationally expensive. Together, these limitations suggest a broader gap: earables have not yet been fully developed as integrated platforms for high-quality output, human-centered sensing, and unobtrusive interaction.

To address this gap, we explore audio as a unifying modality for earable computing. Audio is the most native and widely available channel on earables, requiring no additional sensors or hardware modifications. More importantly, it provides a shared signal space that connects the device, the human body, and the individual user. Building on this insight, we adopt an audio-centric approach to enhance earable usability across multiple levels. At the device level, we model and compensate for acoustic distortions to improve playback quality on commodity earphones. At the human level, we extract subtle physiological signals such as breathing patterns from noisy acoustic observations. At the user level, we leverage individual-specific characteristics embedded in audio to enable passive and lightweight authentication. Rather than adding new sensors, we rethink how audio can be modeled and utilized to unlock the broader earables capabilities.

Next, we present several earable systems (see Figure 1) that demonstrate how audio can serve as a unifying modality across the device, human, and user levels.

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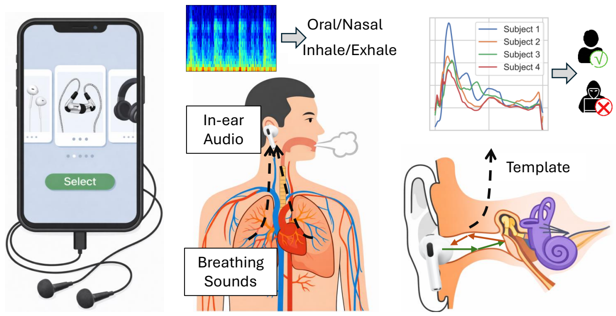

(a) Audio Enhancement (b) Breathing Mode Monitoring (c) Authentication

Fig. 1: **Audio-based earable systems.**

2 Audio-Centric Earable Systems

Audio Playback Enhancement. Low-end earphones are widely used due to their affordability, yet their limited hardware often results in poor audio quality. Existing equalization-based methods can only partially address this problem, as they rely on simplified frequency response modeling and fail to capture complex real-world distortions. To overcome this limitation, we propose a device-aware two-stage learning framework that first models how a target earphone alters audio during playback, and then learns to adjust the input signal accordingly [3]. This enables digital compensation for hardware imperfections without modifying the device.

Breathing Mode Monitoring. Earables provide a promising way to sense human physiological states through acoustic signals. While prior work has mainly focused on coarse metrics such as breathing rate, richer patterns such as breathing modes are much harder to capture in dynamic and noisy conditions. To address this, we use the dual-microphone setup in earables, where the in-ear microphone captures body-conducted breathing sounds and the out-ear microphone provides a reference for environmental noise [1]. By jointly modeling both signals, the system enables robust fine-grained breathing sensing during running.

Implicit User Authentication. As earables increasingly support privacy-sensitive applications, passive and unobtrusive user verification becomes important. Existing approaches often require explicit user actions or remain sensitive to noise, motion, and deployment conditions. To address these challenges, we explore an audio-based authentication approach that leverages user-specific acoustic characteristics introduced by the occluded ear canal [2]. By modeling sound transformations across digital and microphone signals, the system captures stable identity cues and enables lightweight authentication without explicit user input.

Together, these systems illustrate a shared audio-centric view of earable computing, where audio connects device output, human sensing, and user interaction.

3 Roads Ahead

Our work points to a broader future for earables as continuous, human-centered computing platforms. A key next step is to move from isolated functions to integrated systems that jointly support playback, sensing, and interaction within an audio-centric pipeline. This requires addressing multi-task interference, resource sharing, and real-time processing on resource-constrained devices. Meanwhile, diverse earable form factors, including open-ear and emerging designs, introduce new opportunities and constraints for audio-based systems. Future work should explore shared audio representations and lightweight models that support multiple tasks simultaneously, enabling more robust real-world deployment.

4 Short Biography

Changshuo Hu is a Ph.D. candidate in Computer Science at Singapore Management University, advised by Professor Archan Misra and Dong Ma. His research interests lie broadly in mobile and ubiquitous computing, with a particular focus on earable computing, human sensing, and audio-based systems. Beyond audio-centric earable systems, one recent effort is a comprehensive earable survey [5], which reviews research since 2022 and summarizes recent progress in applications, platform capabilities, and future challenges and opportunities. He also introduced a dual-wrist PPG dataset [4] to study motion-induced signal distortions during high-intensity and non-periodic exercise. He received the IMWUT Vol. 8 Distinguished Paper Award and the BodySys 2025 Best Paper Award. Homepage: https://laserhu.github.io/profile/

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