OpenEarable 2.0: Open-Source Earphone Platform for Physiological Ear Sensing

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TOBIAS RÖDDIGER, Karlsruhe Institute of Technology, Germany
MICHAEL KÜTTNER, Karlsruhe Institute of Technology, Germany
PHILIPP LEPOLD, Karlsruhe Institute of Technology, Germany
TOBIAS KING, Karlsruhe Institute of Technology, Germany
DENNIS MOSCHINA, Karlsruhe Institute of Technology, Germany
OLIVER BAGGE, Karlsruhe Institute of Technology, Germany
JOSEPH A. PARADISO, Massachusetts Institute of Technology, United States
CHRISTOPHER CLARKE, University of Bath, United Kingdom
MICHAEL BEIGL, Karlsruhe Institute of Technology, Germany

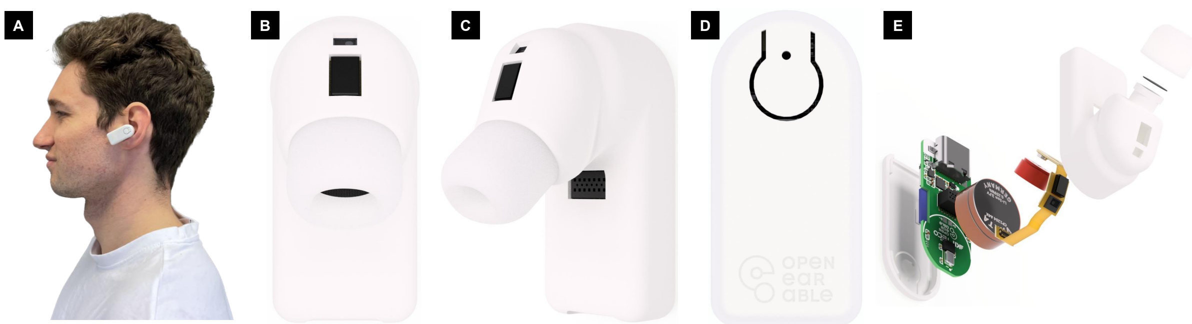

Fig. 1. (A) a user wearing OpenEarable 2.0; (B) the front view of the device revealing a pulse oximeter and optical temperature sensor; (C) the frontal-right view of the device showing its shape and extension connector; (D) the back view of the device showing the push button and microphone hole; (E) an explosion rendering of OpenEarable 2.0, revealing three microphones (inside the ear canal, external facing, and bone-conduction), a pressure sensor, a 9-axis IMU for measuring head movements, a 3-axis accelerometer for measuring movement in the ear canal, a coin cell battery, a speaker and a dual-core LE Audio capable microcontroller.

Earphones have evolved from pure audio devices to "earables" that are capable of advanced sensing. Bespoke research devices have shown the unique sensing capabilities of the earable platform; however, they are hard to replicate and require expertise to develop in the first place. In this paper, we present OpenEarable 2.0 – an open source, unified platform that integrates a larger

Authors' addresses: Tobias Röddiger, tobias.roeddiger@kit.edu, Karlsruhe Institute of Technology, Germany; Michael Küttner, michael.kuettner@kit.edu, Karlsruhe Institute of Technology, Germany; Philipp Lepold, philipp.lepold@kit.edu, Karlsruhe Institute of Technology, Germany; Tobias King, tobias.king@kit.edu, Karlsruhe Institute of Technology, Germany; Dennis Moschina, moschina@teco.edu, Karlsruhe Institute of Technology, Germany; Oliver Bagge, bagge@teco.edu, Karlsruhe Institute of Technology, Germany; Joseph A. Paradiso, joep@media.mit.edu, Massachusetts Institute of Technology, United States; Christopher Clarke, cjc234@bath.ac.uk, University of Bath, United Kingdom; Michael Beigl, michael.beigl@kit.edu, Karlsruhe Institute of Technology, Germany.

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number of sensors for conducting comprehensive earable research. OpenEarable 2.0 works as regular binaural Bluetooth earphones and features two ultrasound capable microphones (inward/outward), a 3-axis ear canal accelerometer/bone microphone, a 9-axis head inertial measurement unit, pulse oximeter, optical temperature sensor, ear canal pressure sensor, and microSD card. These capabilities allow for the detection and measurement of 30+ phenomena on the ear that can be used across a wide range of applications in health monitoring, activity tracking, human-computer-interaction and authentication. We describe the design and development of OpenEarable 2.0 which follows best open hardware practices and achieves commercial-level wearability. We provide justification for the selection and placement of integrated sensors and include in-depth descriptions of the extensible, open source firmware and hardware that are implemented using free to use tools and frameworks. For real-time sensor control and data recording we also contribute a web-based dashboard and mobile smartphone app. The wearability and ability to sense different phenomena are validated in four studies which showcases how OpenEarable 2.0 provides accurate measurements in comparison to established gold-standard measurements. We further demonstrate that OpenEarable 2.0 can be assembled by inexperienced users, and that undergraduate students can build applications using the OpenEarable platform.

CCS Concepts: • **Hardware → Emerging technologies**; • **Human-centered computing → Ubiquitous and mobile computing systems and tools**; **Ubiquitous and mobile devices**;

Additional Key Words and Phrases: earphones; in-ear; earables; hearables; open-source; open hardware; open wearables; hearing aid

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1 INTRODUCTION

Earables (also known as *hearables*) are electronic devices that are worn in, on, or around the ear. They are an evolution of traditional ear-based devices such as earphones, headphones, or hearing aids that can sense and measure phenomena beyond, and in addition to, providing conventional audio functionalities [56, 108]. Earables benefit from the fact commercial ear-based devices have already established social acceptability of ear-worn devices, and the unique position of the ear allows for the accurate measurement of a range of physiological signals and movements that can provide comprehensive insights into skeletal, muscular, nervous, cardiovascular, respiratory, and digestive systems [108]. These can be sensed using a wide range of different sensing modalities, ranging from inertial measurement units to optical-based sensors such as photoplethysmography (PPG) or infrared thermometry, that can be used independently or combined to enable unique sensing opportunities. As a result, earables have the potential to be one of the most important wearable technology platforms to revolutionize a wide range of applications from health [54, 88, 112] and activity tracking [16, 107, 116], to interaction [68, 109, 129] and authentication [39, 43, 87].

One of the biggest challenges facing the earable community is the requirement for bespoke, miniaturised, and specialist hardware in order to push the boundaries of earable research and explore what can be sensed on the ear. Several earable survey papers have highlighted how earable research needs to demonstrate and validate that these phenomena can be sensed and applied in ecologically valid settings [31, 75, 104, 108]. For earable devices, applications can vary greatly as traditional earphones have found many applications and are seen as durable and rugged devices. Transitioning from basic lab-based proof of concepts with bulky devices and wired technologies to small form factor, ergonomic, wireless devices is non-trivial which is further complicated when multiple sensing modalities must be combined on the same earable platform. Initiatives such as eSense [56] provide the opportunity for researchers to start exploring basic sensing modalities on the ear and have spurred a multitude of discoveries [102]. More recently, commercial devices have begun to offer high quality, ergonomic earables that provide access to individual sensors (e.g. AirPods Accelerometer [50], Liberty Pro Photoplethysmography [27]).

However, despite these advances, there is currently no platform that integrates a large number of sensors simultaneously for conducting comprehensive novel multi-modal earable sensing research.

To address these issues and catalyze research in the earable space we introduce OpenEarable 2.0 – the first fully open-source earable device which features the largest number of sensors on a single earable platform. OpenEarable 2.0 combines wireless binaural earphones that support Bluetooth LE Audio [19] with a 9-axis inertial measurement unit for measuring head movement, 3-axis ear canal accelerometer which doubles as a bone-conduction microphone, pulse oximeter, optical temperature sensor, pressure sensor, inward and outward-facing ultrasound-capable microphones, and ultrasound-capable speaker. As a result, OpenEarable 2.0 is capable of detecting the majority of phenomena that can be sensed on the ear, as identified by Röddiger et al. [108] (see Figure 2). OpenEarable 2.0 is designed to be a powerful tool for researchers to enable ecologically valid data collection in-the-wild. They feature an ergonomic form factor and the ability to run continuously for five hours with all sensors and audio streaming enabled on a single charge. Sensor data is streamed via Bluetooth Low Energy (BLE) with several data logging options for different use cases. We contribute easy-to-use software to record and log data from OpenEarable 2.0 devices including a web-based dashboard and a cross-platform mobile Flutter app for iOS and Android. OpenEarable 2.0 also has a microSD card for storing data offline and supports edge-ml [118], a no-code embedded machine learning framework. OpenEarable 2.0 is designed to increase and strengthen the earable community by empowering new users to develop and deploy earables applications, while allowing technologists to extend and build upon the platform. As a result, OpenEarable 2.0 follows best practices from the Open-Source Hardware Association (OSHWA) [96] and includes a 14-pin header connector and a 12-pin FPC connector for hardware extensibility. The OpenEarable 2.0 firmware is based on *Zephyr OS* [130], an open-source embedded real-time operating system, and is therefore easy to modify and expand.

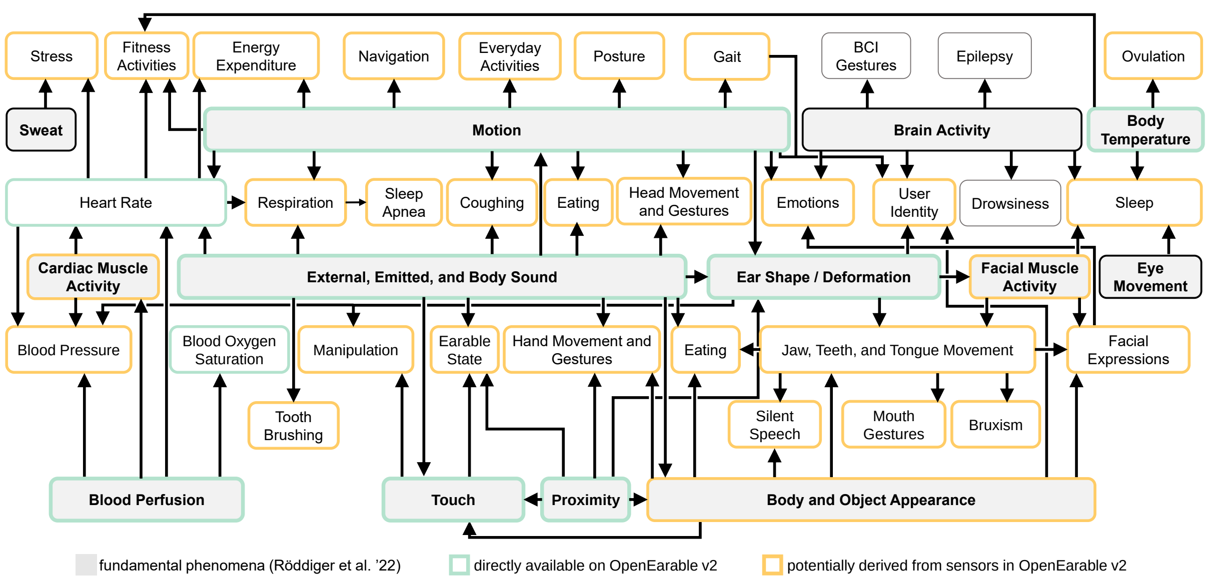


Fig. 2. Flow diagram by Röddiger et al. [108] that shows the relationship between different phenomena obtained from the ears. The grey boxes represent "fundamental" phenomena that can be directly sensed and from which all other phenomena can be derived. The colorized borders show the phenomena that can be sensed with the OpenEarable 2.0 platform.

In this paper, we discuss the design of OpenEarable 2.0 and the underlying requirements that underpin the platform. For replicability, we describe the hardware and system architecture in-depth and provide justification for the selection and placement of components. This is followed by assembly details and instructions that, combined with supplementary video and hardware design material, will allow others to manufacture and build their own OpenEarable 2.0. We also provide an overview of the firmware that underpins OpenEarable 2.0, and the software applications that can be used to extract the data. In a system evaluation with users, we showcase the wearability and sensing capabilities in four user studies that show how OpenEarable 2.0 can detect motion activities, heart rate, blood oxygen, and body temperature close to medical-grade gold-standard measurements. We further demonstrate that OpenEarable 2.0 can be easily assembled by users with no prior experience and that 54 undergraduate students can make effective use of the earable platform.

OpenEarable 2.0 provides a platform for more robust, integrated, and ecologically valid earable research. With the ability to sense more than 30 phenomena from the ears that can be used for a wide variety of applications, OpenEarable 2.0 can spur a wealth of new research and create many opportunities for sensor fusion and long-term earable studies. In sum, we contribute the following:

(1) OpenEarable 2.0 – an ergonomically designed open-source wireless earable platform for physiological sensing in both lab and field settings;
(2) Open-source earable firmware and accompanying software ecosystem including a web-dashboard and mobile cross-platform app to control the device and record sensor data;
(3) Empirical evidence to show OpenEarable is an ergonomic and socially acceptable device compared with state-of-the-art commercial ear-based devices;
(4) Validation of OpenEarable 2.0's sensing capabilities in terms of accuracy and precision against non-ear based, established gold-standard measurements.
(5) Demonstration of the usage of OpenEarable 2.0, showing that OpenEarable 2.0 can be assembled with ease and that it lowers the entry barrier into earable computing for undergraduate students.

2 RELATED WORK

Earables have emerged as their own wearable category with research maturing to a point where a number of review papers discuss the wide variety of sensing opportunities and applications [31, 76, 89, 104, 108]. Earables are ideally located to sense a wide variety of phenomena including, but not limited to, bodily functions across nervous [34], endocrine [11], cardiovascular [85], respiratory [112], and digestive [16] systems as well as movement of the user [116], their facial movements [7], and their eye movements [74]. In addition, earables provide a uniquely situated sensing platform for remote sensing of visual [30] or audio phenomena [129]. At a higher level, all of these phenomena can be used across a broad spectrum of applications, ranging from physiological and health monitoring, movement and activity recognition, human-computer-interaction, and authentication and identification [108]. This positions earables as a promising wearable category similar to smartwatches.

Despite the potential of the earable platform, the hardware landscape remains fragmented with a noticeable absence of commercial platforms that integrate a wide range of sensors. Table 1 provides a comprehensive overview of various platforms along with their capabilities. Among these, Apple AirPods stand out in the commercial sector as a major platform, offering access to the Inertial Measurement Unit (IMU). The Liberty 4 earbuds are noteworthy for their ability to monitor the user's heart rate. The PineBuds Pro [103] hard- and firmware are partially open-source but they lack any sensing capabilities. For the sake of simplicity, other commercial platforms with similar sensors are not listed. A common drawback among commercial platforms is the number of sensors, the closed firmware and hardware as well as limited access to microphones. The *c-med° alpha* [32] stand out as a device because they are certified for medical use cases, however, they are not intended to be used as everyday earphones with audio capabilities.

Table 1. Comparison of capabilities and specifications of different ear-based sensing devices according to Bluetooth Audio (BT A.), Microphone (Microph.), Inertial Measurement Unit (IMU), Photoplethysmography (PPG), Optical Temperature Sensor (Temp.), barometric pressure sensor (Bar.), Internal Memory (Mem.), external application programming interface for data access (API), firmware open-source (FW), hardware open-source (HW), and battery life on a full charge (Batt.).

Name	**BT A.**	**Microph.**	**IMU**	**PPG**	**Tem.**	**Bar.**	**Mem.**	**API**	**FW**	**HW**	**Batt.**
AirPods Pro [50]	Yes	In 1; Out 2	6-axis	No	No	No	-	Partly	Closed	Closed	6 h
Liberty 4 [27]	Yes	In 1; Out 1	6-axis	Yes	No	No	-	Partly	Closed	Closed	9 h
PineBuds Pro [103]	Yes	In 1; Out 2	None	No	No	No	-	Open	Open	Partly	5 h
c-med° alpha [32]	No	In 0; Out 0	3-axis	Yes	No	No	-	Partly	Closed	Closed	15 h
eSense [56]	Yes	In 0; Out 1	6-axis	No	No	No	-	Open	Closed	Closed	1.2 h
OmniBuds [86]	Yes	In 1; Out 2	9-axis	Yes	Yes	No	2GB	Open	Closed	Closed	6 h
ClearBuds [29]	Yes	In 0; Out 1	3-axis	No	No	No	1GB	Open	Open	Open	40 h
OpenEarable [110]	No	In 1; Out 0	6-axis	No	No	Yes	-	Open	Open	Open	4 h
OpenEarable 2.0	Yes	In 1; Out 1 Bone: 1	9-axis 3-axis	Yes	Yes	Yes	microSD	Open	Open	Open	8 h

In the research community, the availability of the *eSense* [56] platform, developed by Nokia Bell Labs, has been instrumental in advancing earable research. The eSense platform integrated an array of sensors into an ergonomic earbud design, coupled with extensive APIs, allowing researchers to collect data and develop unique applications. More recently, Nokia Bell Labs have released the *OmniBuds* [91] platform as a successor to eSense. This expands on the available sensors and focuses on processing sensor data on-board using a real-time operating system that includes machine learning capabilities. Omnibuds is the closest example to OpenEarable 2.0 in terms of the sensing functionality the platform provides, with similar approaches for sensor placement (e.g. PPG and temperature locations). In addition, OmniBuds are packaged more as a “finished” product with an injection-molded form factor. However, at the time of writing the supply of Omnibuds is limited to a select group of researchers and the hardware and firmware are closed source, mirroring some of the constraints observed in commercial offerings. We contrast this in our approach to OpenEarable 2.0 which can be manufactured by anyone with basic hardware skills and the platform is specifically designed to be extended with custom hardware using the available connectors.

ClearBuds laid the foundation for democratizing ear-based sensing hardware [29]. OpenEarable built upon this and presents the closest example in terms of philosophy – open to all and extensible [110]. While this demonstrated the potential for an open source earable platform, it is limited to a small number of sensors and, as it was primarily focused on input sensing, does not provide wireless earphone capabilities which limits the deployability in real-world usage scenarios. OpenEarable 2.0 continues with the open source, extensible philosophy but provides a more integrated and mature sensing platform with comprehensive and integrated multi-modal sensing capabilities, that can also be used as a pair of regular Bluetooth earphones with the functionalities users expect from a pair of earphones.

3 DESIGN PROCESS

In this section, we discuss the guiding principles that underpinned the development of the *OpenEarable* platform and the sensor selection process.

3.1 Guiding Principles

Our vision is that *OpenEarable* is a general-purpose hardware sensing platform for the earables research community that can facilitate high quality research and development. To do so, we incorporate guidelines from the Open Source Hardware Association (OSHWA) [96] and apply best practices by (i) sharing all original hardware design source files and ready-to-view outputs (e.g. PDFs); (ii) using freely available tools, common production processes and widely available components for all designs; (iii) open-sourcing all firm- and software; (iv) sharing photos and instructions how to make and use the hardware; (v) licensing all resources under MIT license.

3.1.1 Openness and Extensibility. All *OpenEarable* hardware (including design files), firmware and software (including data recording tools) are open and easily extensible, and the tools used are specifically selected to be free-of-charge for the entire design and development process. We believe that as many people as possible should be able to modify and expand the platform in unique and novel ways. To this extent, *OpenEarable* provides the core infrastructure that enables the exploration of different sensing paradigms. For extensibility, OpenEarable 2.0 has a 14-pin header connector and a 12-pin FPC connector, and an easy to setup and modify software ecosystem.

3.1.2 Manufacturability and Cost-Effectiveness. To increase the potential adoption of *OpenEarable* we made design choices to reduce the complexity of manufacturing and allow researchers to build the device at an affordable cost. Therefore, we selected off-the-shelf components which are readily available from major suppliers, and designed the printed circuit boards (PCBs) so that they can be ordered fully-assembled from a self-service PCB assembly manufacturer. In addition, no specialized manufacturing tools are required and all plastic parts are designed to be 3D-printable with a Stereolithography 3D printer (SLA). These printers are commonly available in research and maker labs, and it is possible to order printed parts online if a physical printer is unavailable.

3.1.3 Attachment, Comfort, and Wearability. Earable research should be ecologically valid to provide valuable real-world insights in naturalistic settings. To enable this, OpenEarable 2.0 is designed for everyday use so that it can be easily and comfortably attached while being stable and robust against user movement. To accommodate this, we designed OpenEarable 2.0 with a similar form factor to *AirPods Pro*. The device supports different eartip sizes to accommodate a variety of ears. All edges of OpenEarable 2.0 are rounded off to maximize comfort, and the bulk of the device sits inside the concha, which is mechanically stable and avoids undue pressure on the more sensitive inner ear. While the ears possess relatively unique features the overall shape of the auricle is shared among users [15]. Ban and Jung [15] analyzed ear shape of 310 participants for ergonomic product design and across all users they found a mean ear height of 58.9 mm (SD: ±4.6 mm, Korean) and 57.7 mm (SD: ± 4.2mm, Caucasian), mean ear depth (distance between auricle and head) of 17.2 mm (SD: ±3.1 mm, Korean) and 15.2 mm (SD: ±3.0 mm, Caucasian), mean concha width of 17.4mm (SD: ±2.8 mm, Korean) and 16.7 mm (SD: ±2.9 mm, Caucasian), and mean concha height of 15.9mm (SD: ±1.5 mm, Korean) and 15.2 mm (SD: ±1.2 mm, Caucasian). We used these values to inform the physical dimensions of OpenEarable to support a large variety of physical ear sizes. The wearability of OpenEarable 2.0 is evaluated in subsection 6.1.

3.1.4 Look and Feel. Within the general consumer domain, *OpenEarable* represents an extension of smart devices such as smartphones and smart watches. In this domain, runtime requirements, hardware and software stability, and professional look and feel are very important. For example, the seminal work of Don Norman [94] has shown that professional design coupled with good look and feel influence general trust in a system. In fact, design has been shown to be even more influential than functionality and usability. This is best explored with software products (e.g., [21]), but also with overall services [8]. Therefore, OpenEarable 2.0 is designed with look and feel in mind.

Table 2. Sensors and their location inside OpenEarable 2.0, as well as the applications they enable based on Röddiger et al. [108].

Sensor	Fundamental Phenomena	Location	Applications
Accelerometer	Motion	Concha (lateral)	Respiration, Emotions, Coughing, Bruxism, Activity Recognition, Step and Repetition Counting, Energy Expenditure, Performance Feedback, Posture, Gait, Navigation, Eating, Head Gestures, Passcode, Motion Authentication
Accelerometer	Motion	Canal entrance	*All of the above*, Facial Muscle Activity, Mouth Gestures, Silent Speech, Jaw/Teeth/Tongue Movements
Gyroscope	Motion	Concha (lateral)	Respiration, Coughing, Bruxism, Activity Recognition, Step and Repetition Counting, Performance Feedback, Posture, Navigation, Eating, Head Gestures
Magnetometer	Motion	Concha (lateral)	Navigation
2 × (Ultra-/Infrasound) Microphone	External, body & emitted sound	Into ear canal; In front of ear	Heart Rate, Respiration, Eating, Drinking, Food Type, Teeth Burshing, Emotion, Coughing, Face, Touch, Wearable Sate, Hand Gestures, Tongue Gestures, Teeth Gestures, Facial Expressions, Motion Authenticatio, Ear-Shape Authentication
Bone-Cond. Microph.	Body sound	Canal entrance	*To be determined*
Photoplethysmography	Blood Perfusion	Concha	Heart Rate, SpO2, Respiration, Stress, Sleep Apnea, Energy Expenditure, Eating
Infrared Thermometry	Body Temperature	Concha	Body Temperature, Ovulation
Barometer	Ear Deformation	Enclosed in canal	Blood Pressure, Eating, Tensor Tympani Contraction, Jaw/Tongue Gestures
Button	Touch	Concha (lateral)	Input
BLE RSS	Proximity	Concha (lateral)	Navigation, Head Pointing

3.2 Sensor Selection and Placement

Röddiger et al. [108] provide a comprehensive overview of the different types of sensors that have been used on the earable platform which were classified into six overarching sensor types: motion, audio, optical, biopotential, environmental, and electric. We use this prior literature to inform the design and placement of sensors on OpenEarable 2.0 which are detailed in Table 2, and which we describe in more depth in the subsequent subsections. OpenEarable 2.0 features all five sensor types with the exception of biopotential because there are currently no standardized hardware components that can be directly integrated. A major challenge of miniaturized earphones is battery life. For example, the popular Apple AirPods Pro last up to 6 hours [50]. We specifically selected sensors in order to maximize the battery life of OpenEarable 2.0 which can support up to eight hours of audio playback and five hours when all sensors are enabled.

In total, OpenEarable 2.0 can detect nine of the thirteen fundamental phenomena identified by Röddiger et al. [108] (five via direct sensing, four indirectly), with the scope to derive 30+ higher level phenomena from these fundamental phenomena (see Figure 2). The specific sensor components were selected based on availability, their size for integration in a small wearable device and high performance based on test breakouts we designed. It was ensured that the sensors can be ordered in small quantities (i.e., not necessary to order a full reel). In addition, sensors were selected based on the intended power architecture (1.8V and 3.3V) and logic level for communication (1.8V). We selected high quality sensors because one of the main application areas of *OpenEarable* is health where high accuracy and precision are critical to enable reliable use. In the following sections, we provide justification and detailed rationale about the selection of specific sensors to detect targeted phenomena, as well as the strategic positioning of these sensors relative to the ear to maximize feasibility and optimize performance.

3.2.1 Motion. Many different types of motion can be sensed on the earable platform using a combination of accelerometers, gyroscopes, and magnetometers, from macro movement of the user walking [52, 53] and performing activities [83], to micro movements which can be used to compensate for motion artefacts when measuring heart rate [95]. Accelerometers have been more extensively used on the earable platform than gyroscopes as they have lower power consumption, but are commonly used in conjunction with gyroscopes [108]. As a result of the small form factor of earables, magnetometers have been problematic because of the electromagnetic noise generated by the speaker. However, these issues can be reduced with calibration methods [40]. Unlike previous devices which utilise 6-axis inertial measurement units (IMUs), OpenEarable features a 9-axis IMU positioned laterally to the concha, placing it away from the electromagnetic speaker to minimize interference. In addition, there is a 3-axis accelerometer at the entrance of the ear canal to provide ear canal motion sensing capabilities, e.g., to detect jaw clenching [20]. The integration of two motion units allows OpenEarable 2.0 to cover the full breadth of motion sensing opportunities, from globally tracking head movements to detecting local ear canal deformations.

3.2.2 Audio. Audible, infrasound, and ultrasound microphones have been used for sensing on the ear, which can be used for heart-rate sensing [26, 37], detection of eating events [6], and ear canal deformation which can be used to infer facial gestures [108]. Different applications have utilised these in different locations on the ear for different applications and in some cases multiple microphones are used. For example, an internal microphone can be used for signal detection of eating events [6], while an external microphone filters surrounding audio [81, 100]. In addition, the combination of a speaker and a microphone can be used to probe the ear canal of a user for authentication [43, 69]. As a result, OpenEarable 2.0 features both internal and external microphones that are both capable of measuring ultrasound, human audible sound and also low frequency infrasound sound effects produced by occlusion effects (e.g., in-ear heart rate tracking [111]). OpenEarable 2.0 also integrates a wide-range audio driver. The concha accelerometer selected for OpenEarable 2.0 is capable of sensing bone-conducted audio signal vibrations, which has not been widely explored in previous earable research and creates a novel opportunity for further exploration. With the integration of these three microphones, OpenEarable 2.0 covers the full breadth of ultra-, infra-, and audible-audio sensing in and outside the ear, conducted via air or bone.

3.2.3 Optical. Optical-based sensors come in many different forms and have been used for detecting blood perfusion [33], cardiac muscle activity [124], and body temperature [97], as well as for facial activity [5], ear deformation [59], and proximity of objects to the ear [82]. We incorporate a photoplethysmography (PPG) sensor which has been used extensively in the literature for directly sensing blood perfusion in the ear, which can in turn can be used to infer cardiac muscle activity [124], as well as an infrared thermometer which can be used to measure body temperature. PPG sensors are available with different LED wavelengths. To cover the full range, OpenEarable 2.0 features a state-of-the-art PPG module that supports red, infrared, green, and ambient light emission and detection. We place the PPG sensor at the concha because prior work has shown this location provides the best trade-off between sensing accuracy, feasibility of integration into an earbud form factor, and resilience against motion artifacts compared to PPG in or behind the ear canal [41].

Optical proximity sensors have been used to detect nearby objects which can be used as an input channel for interaction [82] and infer the wearable state of the earable device [78]. The PPG sensor inside OpenEarable 2.0 also has a proximity mode. Further, there is scope to include capacitive sensing by connecting capacitive electrode surfaces to one of the available pins on the 14-pin header connector which can also be used to infer proximity of external sources. Standard RGB cameras have also been explored on the ear for internal sensing similar to an otoscope [49], as well as outward facing cameras that can be used for a variety of sensing [30]. However, RGB cameras are computationally intensive devices with high power consumption that would require significant components and bulk to be added to the hardware device. As a result, we opted not to include these and instead optimise OpenEarable 2.0 for applications that allow longer-term deployments.

3.2.4 Environmental. Basic environmental characteristics including temperature, humidity, and air pressure can also be sensed on the ear. Uniquely, the internal air pressure inside the ear canal has been leveraged as a sensing principle to detect facial activities [7] and for novel interaction by sensing contraction of the tensor tympani muscle [109]. As a result, the OpenEarable 2.0 platform features an in-ear pressure sensor located in the ear canal for sensing ear deformation that can be used to infer facial movements. Simultaneously, this sensor can be used to track ambient pressure changes if the eartips do not perfectly seal the ear canal. An ambient temperature thermistor is included in the pressure sensor but currently not used. Instead, we have implemented an optical temperature sensor into the concha, which was found to have similar performance to a temperature sensor pointing at the eardrum [61], which is a widely accepted gold-standard position [24]. A temperature sensor pointing at the eardrum or in the ear canal is not feasible because it would block the audio path and interfere with the silicone eartips. In addition, pointing a sensor at the tympanic membrane requires per-user calibration because of ear canal shape differences and orientation of the sensor toward the tympanic membrane [17, 77]. A hygrometer is not included because there is a lack of evidence to underpin its usefulness in earable applications.

3.2.5 Electrical. Electrical characteristics such as piezoelectric effect, resistivity, and capacitance can be used to sense deformation of the ear canal [79], the ear itself [68], or be used to infer touch and proximity of other objects [128]. Signal strength of electromagnetic radiation such as the Bluetooth signal can also be used to infer proximity between two electronic devices [48]. In addition, basic functionality such as a button can be used to infer touch and control the device itself. We incorporated a basic push button into OpenEarable 2.0 with scope to easily incorporate capacitive sensing, leaving this extensible to allow researchers to choose their own form factor for the capacitive electrode surface.

4 HARDWARE

The hardware development process for OpenEarable 2.0 was iterative and modular. Initially, we leveraged both custom-designed and commercially available breakout boards to validate concepts and functionalities progressively. We then transitioned to fully custom PCBs that integrate the required circuitry and which fit the desired form factor. In the following, we describe the electronic hardware of OpenEarable 2.0 and its mechanical design. We introduce the specific properties of the different sensors and also provide details about the manufacturing and procurement process.

4.1 Electronics

The following sections introduce the electronics of OpenEarable 2.0 including the conceptual architecture, the printed circuit boards, and the different components and sensors including their properties.

4.1.1 Architecture. Figure 3 shows the schematic architecture of OpenEarable 2.0, consisting of two parts: the main rigid PCB that is placed in front of the ear and the flex PCB that folds into concha and ear canal. The two PCBs are connected via a 12-positions FPC connector (BM46B-12DS) with a number of leads suitable for various sensors (1.8V, 3.3V, GND, GPIO, I²C, PDM, $\text{Speaker}_{\text{OUT}}$, SoftSerial, SoftSPI), but also generic enough to be suitable for the replacement with customised flex PCBs, closely related to earpieces for OpenEarable 1.3 [61, 111].

The main PCB entails the microcontroller, power management, a coin cell battery, an RGB LED and controller, the audio amplifier, a microSD card slot, and a 9-axis inertial measurement unit (IMU), consisting of a 3-axis accelerometer, gyroscope, and magnetometer, the outward facing ultra- and infrasound-capable microphone, and the ultrasound-capable speaker. The flex PCB of OpenEarable 2.0 has various sensors: the inward ultra- and infrasound-capable microphone [111], a pulse oximeter, an optical temperature sensor, a pressure sensor, a 3-axis bone-conduction microphone accelerometer. The different components communicate via standard embedded protocols: Serial via USB for programming, I²C for sensor communication, I²S for outgoing audio transmission,

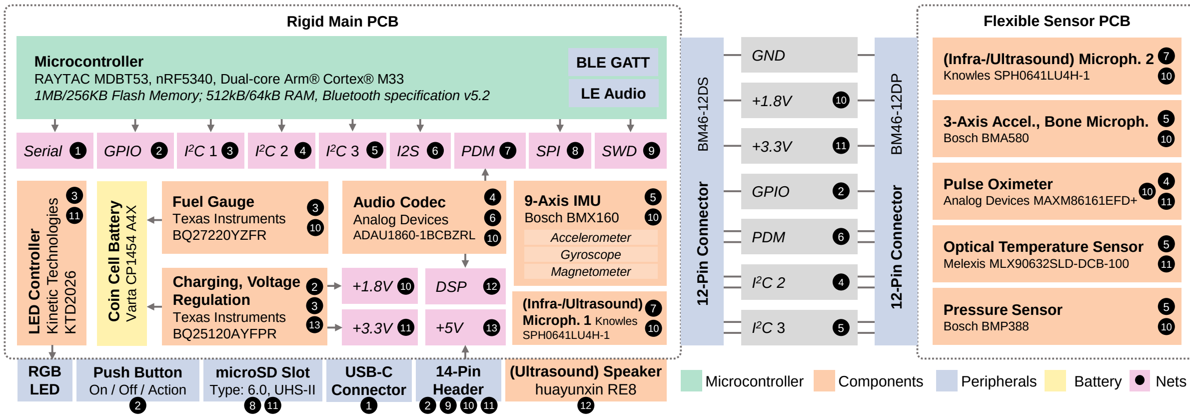


Fig. 3. Overview of the OpenEarable 2.0 hardware architecture, detailing the various components such as the sensors, microcontroller and battery, alongside a schematic representation of the connections (nets) between components. The architecture also includes external peripherals for interfacing with OpenEarable 2.0.

PDM for the digital microphones, and SPI for the microSD card. Serial Wire Debug (SWD) can be used for programming and debugging. The system operates at 1.8 V. The RGB LED, the pulse oximeter, and the optical temperature sensors also require an additional 3.3 V supply. A 14-pin header connector gives access to the hardware and allows for further easy extension and modification of the architecture (1.8V, 3.3V, GPIO, I²C, PDM, SoftSerial, SoftSPI, SWD of microcontroller and audio DSP). The microcontroller supports BLE GATT and LE Audio (see details in subsubsection 4.1.3) for wireless communication.

4.1.2 Printed Circuit Boards. Two Printed Circuit Boards (PCBs) were designed to fit into a form factor suitable for wearing on the ears. For the development of all design files we use the free, web-based tool *Easy EDA (Pro Edition)* [36]. The PCB that goes in front of the ear is a rigid, 4-layer PCB (1.4 mm thick) and is designed to be worn on either the left or right ear interchangeably. Vias are plugged with epoxy and covered with copper because the PCB includes several BGA (Ball Grid Array) components, such as the charging controller. A flexible, 2-layer PCB (0.11 mm thick) is designed to fold into the concha. This flex PCB can be used interchangeably for both the left and right ears. The flex PCB has a series of stiffeners for better stability and easier assembly. Both PCBs can be fully manufactured by *JLCPCB* using their standard assembly process, which includes the placement and soldering of all components onto the PCBs, and for health and environmental reasons we used lead-free solder for the assembly. All PCBs are fully tested automatically using a flying probe test. Parts for the assembly were selected to be available directly through *JLCPCB* or via their parts procurement process, which takes approximately two weeks until parts become available. If all parts are available, manufacturing a small batch of 10 PCBs through *JLCPCB* takes about one week. For PCB self assembly, a stencil can be ordered from *JLCPCB* to apply the solder paste and subsequent component soldering using a suitable soldering oven. Please note soldering the PCB from scratch yourself is not recommended. The PCBs' design files (schematics and layouts) are available under the MIT license. The mechanical design and assembly of OpenEarable 2.0 are described in subsection 4.2.

4.1.3 Microcontroller: RAYTAC MDBT53-1M, nRF5340 [105]. OpenEarable 2.0 integrates the RAYTAC MDBT53-1M module that is built around the nRF5340 microcontroller. This microcontroller unit (MCU) has a dual-core configuration featuring Arm® Cortex® M33 processors with 1MB/256KB flash memory and 512kB/64kB RAM for

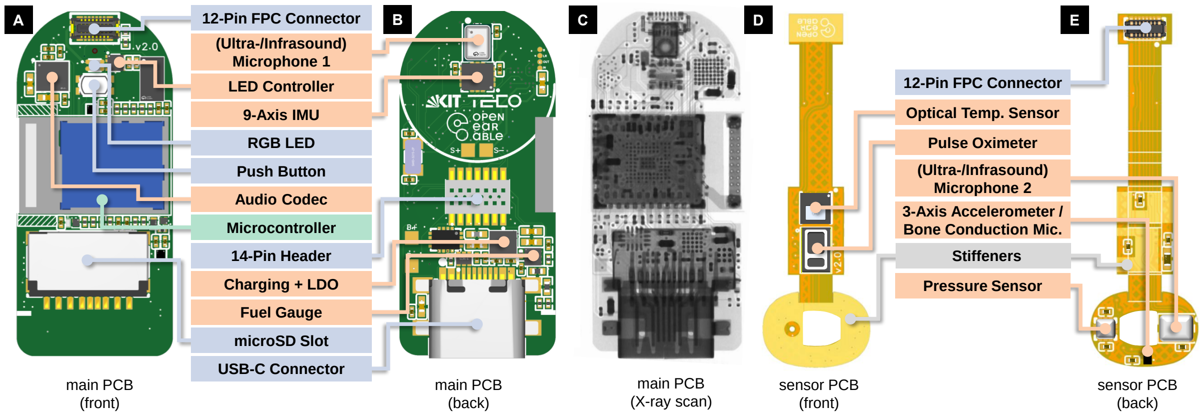


Fig. 4. Overview of the different OpenEarable 2.0 PCBs. (A) front view of the main PCB; (B) back view of the main PCB; (C) X-ray scan of the main PCB revealing the high integration of different traces of the 4-layer PCB; (D) front view of the sensor flex PCB; (E) back view of the sensor flex PCB.

the application and network cores respectively. The application core clocks at 128 MHz and the network core at 64 MHz. The microcontroller supports GPIO, SPI, UART (Serial), I²C, I²S, SWD, and PDM. Moreover, it supports Bluetooth specification v5.4 including BLE GATT (Generic Attribute Profile) that can be used for streaming sensor data and LE Audio for wireless audio transmission [19]. The module has a chip antenna pre-installed and is pre-certified as FCC compliant (US Federal Communications Commission).

4.1.4 Power Management. OpenEarable 2.0 features in-built power management and can be charged using a standard USB Type-C cable that plugs into the main PCB. At room temperature it takes about 2 hours to fully charge the device, and the battery life of different modes is summarized in Table 3. To save power, the firmware of OpenEarable 2.0 automatically disables unused sensors.

Charging Controller and Voltage Regulation: Texas Instruments BQ25120AYFPR [120]. The charging controller integrated circuit (IC) manages the charging process in accordance with the battery specification (refer to the Battery paragraph in section 4.1.4 for details). The IC also transforms the battery's voltage into two power outputs: a 1.8V output generated by the integrated charge pump, which supplies power to most components, and a 3.3V output provided by the built-in Low Dropout Regulator (LDO). Additionally, the chip is equipped with protective features including short circuit protection, time-based overcharge protection, and undervoltage protection (for voltages below 3.0V) to safeguard the battery. Furthermore, the charging IC maintains regular communication with the MCU host at 50 ms intervals to verify system integrity. In the event of a communication failure (e.g., during a fast charging process that necessitates temperature monitoring), it automatically resets to default settings to prevent battery damage. Moreover, OpenEarable 2.0 utilizes the manual reset timer of the charging IC, linked to the push button (see section 4.1.5). The push button needs to be held in the top position for 12 seconds to reset the microcontroller via the charging controller.

Fuel Gauge: Texas Instruments BQ27220YZFR [119]. The fuel gauge monitors the battery's remaining capacity and current consumption for battery charge percentage indication. Furthermore, its internal temperature sensor is utilized to measure the ambient temperature, which informs the charging parameters set by the charging controller. After all parameters are written, the fuel gauge enters a "sealed" state, remaining in this condition until the battery is removed, at which point reconfiguration would be necessary.

Table 3. Lower boundary of the battery life of OpenEarable 2.0 based on the datasheets of the components. Different modes of operation result in different battery life for OpenEarable 2.0. The capacity of the coin cell is 108 mAh equivalent to 400 mW. The 1.8 V charge pump has an efficiency of 92% and the LDO for 3.3 V of 89%. Calculations assume the Varta CP1454 A4X generation.

Component	**Voltage**	**Max. [mA]**	**Sensors + Audio [mA]**	**Audio [mA]**	**Power Off [mA]**
Microcontroller	1.8	15.1	15.1	15.1	0.0009
Antenna	1.8	8.3	8.3	8.3	0
Charge Controller	1.8	0.012	0.007	0.007	0.0009
Fuel Gauge	3.7	0.05	0.05	0.05	0.009
RGB LED	3.7	12	0	0	0
RGB Controller	3.7	0.3	0.3	0.3	0
Audio Codec	1.8	27.8	5.0	5.0	0
(Inf./Ultr.) Microphone 1	1.8	1	0.85	0	0
(Inf./Ultr.) Microphone 2	1.8	1	0.85	0	0
3-axis Accel. (Bone Mic.)	1.8	0.125	0.125	0	0
9-Axis IMU	1.8	1.6	1.6	0	0
Pulse Oximeter	3.3	49.7	3.0	0	0
Pressure Sensor	3.3	1.2	1	0	0
Optical Temperat. Sensor	3.3	1.4	1	0	0
Total [mW]		330 mW	60 mW	41 mW	0.037 mW
Battery Life [h]		1.2 h	6.6 h	9.8 h	453 days

Battery: Varta CP1454 A4X [123]. The battery of OpenEarable 2.0 is a Graphite-layered metal oxide ($LiNo_xMn_yCo_zO_2$) coin cell battery. It has a nominal voltage of 3.7 Volts and a nominal capacity of 108 mAh. The battery can continuously discharge at 2C (approximately 220mA) and can handle up to 3C for brief periods of up to 2 seconds (approximately 330mA) within a temperature range of -20°C to 60°C. When the ambient temperature is between 15°C and 45°C, the battery is charged at a rate of 1C, resulting in a charging duration of about one hour. At lower temperatures, the charging current is adjusted according to the battery's specifications, based on environmental temperature readings from the fuel gauge via the microcontroller. Other generations of the Varta CP1454 are also compatible but have less capacity.

4.1.5 I/O Interfaces. As basic means for interaction with OpenEarable 2.0, the device features a push button and a RGB LED controlled via a dedicated IC.

Push Button: SHOU HAN TS2819A 230GF [4]. The push button can be pressed to trigger interrupts on the microcontroller. It also connects to the charging controller to trigger resets of the microcontroller after the threshold time is reached. The detailed behavior of the button depends on the state of the device and are described in subsubsection 5.1.2.

RGB LED Controller: Kinetic Technologies KTD2026 [60]. OpenEarable 2.0 uses an RGB controller IC to precisley set the current of the RGB channels. Different colors and patterns are used to indicate device states, described in more detail in subsubsection 5.1.2.

4.1.6 Audio. OpenEarable 2.0 supports wireless audio streaming via LE Audio [19]. The digital audio output is forwarded to a digital-to-analog converter for output on the speaker. The two microphones digitize the signal internally and transmit the signal via PDM to the host microcontroller.

Audio Codec: Analog Devices ADAU1860-BCBZRL. The audio processing unit of OpenEarable 2.0 now incorporates the ADAU1860-BCBZRL, a low-power audio codec and two digital signal processors (DSPs). The ADAU1860 supports sample rates up to 768 kHz, providing high-resolution audio suitable for advanced applications, including earable ultrasound [43]. It delivers a signal-to-noise ratio (SNR) of up to 110 dB and a total harmonic distortion plus noise of -95 dB. Operating within OpenEarable 2.0, the ADAU1860 typically outputs audio at 48 kHz and receives input from the microphones. While currently not in use, the integrated Tensilica HiFi 3z DSP core can support advanced audio processing, including filters, equalization, beamforming, and noise cancellation.

Microphone 1 (inward) and 2 (outward): Knowles SPH0641LU4H-1. For OpenEarable 2.0 we selected ultrasound capable microphones that can measure audible and inaudible frequencies which has been proven useful in different earables works [37, 43]. In a recent study, this microphone has also been validated to measure infrasound phenomena, such as heart rate detection based on the occlusion effect [110]. The microphones communicate with audio Codec via Pulse Density Modulation (PDM). One microphone points inside the ear canal and the other to the outside of the wearer. One microphone is sampled at the rising edge and the other on the falling edge of the PDM clock. One microphone can be selected to be streamed via LE Audio with 48 kHz and the other one can be recorded to the microSD card up to 62.5 kHz (see Table 4 for details). OpenEarable 2.0 also incorporates an accelerometer with bone-conduction microphone abilities, detailed in subsubsection 4.1.7.

Speaker: huayunxin RE8, 8 mm, 16 Ohm. The speaker inside OpenEarable 2.0 is a standard earphone driver. It has a rated power of 3 mW, rated impedance of 16 Ω ± 15% and sensitivity of 97 ± 3 dB. It is designed to operate in a frequency range of 20 Hz - 20 KHz but can also produce higher frequencies.

4.1.7 Sensors. The different sensors in OpenEarable 2.0 all support I²C communication at 1.8V logic level. The theoretical maximum sampling rates of the sensors and the maximum sampling rates of each sensor available via BLE GATT are summarized in Table 4 and the power consumption in Table 3. The maximum sampling rates achievable via BLE are dependent on the sampling rates selected across sensors.

3-Axis Accelerometer and Bone-Conduction Microphone: Bosch BMA580 [114]. The ear canal accelerometer is, according to Bosch, the "world's smallest acceleration sensor". It is specifically designed for earable applications, has three axes and is low power while running at 1.8V. It supports high sampling rates (see Table 4) and is suitable to detect voice conducted via bone. In OpenEarable 2.0, we position the sensor at the entrance of the ear canal to make sure it can also detect ear canal deformations.

9-Axis Inertial Measurement Unit (IMU): Bosch BMX160 [113]. The accelerometer, gyroscope and magnetometer of OpenEarable 2.0 are enabled by the Bosch BMX160 9-axis inertal measurement unit (IMU). The sensor preserves space on the PCB because it incorporates three sensors into one footprint, compared to alternative solutions which require multiple components. As a micro-electromechanical system (MEMS) the IMU has very little power consumption operating at 1.8 V. The sampling rate and resolution of the sensor are summarized in Table 4. The IMU is placed on the main PCB in front of the ear and away from the electromagnetic speaker so that no magnetometer interference is minimized.

Pulse Oximeter: Analog Devices MAXM86161EFD+ [35]. The pulse oximeter inside OpenEarable 2.0 is a red, infrared, and green Photoplethysmography (PPG) sensor. The principle behind PPG involves detecting blood volume changes based on light absorbance in the microvascular bed of tissue [3]. The green LED can be used for heart rate monitoring due to its high signal strength for reflective PPG [126] and robustness against artifacts during daily activities [67]. In addition, blood oxygen saturation can be measured using the absorbance differences across multiple light wavelengths [90]. For measuring SpO2, the ratio of the absorbed red to infrared light is calculated. Oxygenated hemoglobin absorbs more infrared light and less red light, whereas deoxygenated hemoglobin absorbs more red light and less infrared light. This ratio is used to determine the blood oxygen saturation level

Table 4. Overview of the supported streaming rates via BLE and LE Audio as well as the properties of the different sensors including their maximum sampling rate, resolution and accuracy.

Sensor	**Component**	**Streaming Rate [Hz]**	**microSD Rate [Hz]**	**Sensor Max. [Hz]**	**Resolution**	**Accuracy**
Microphone 1 Microphone 2	Sound	48k	62.5k	4.8M	Sensitivity: -27 to -25 dBFS	SNR: 64 dB(A)
3-axis Accel.	Acceleration	360	800	6400	16 bit	-
	Bone-Cond. Audio	1000	3200	6400	16 bit	-
9-Axis IMU	Acceleration	120	800	1600	16 bit	-
	Angular Velocity	120	800	3200	16 bit	-
	Magnetic Field	120	800	800	0.3 µT	±2.5 deg
Pulse Oximeter	ADC-Value (Red)	400	800	4096	19 bit	-
	ADC-Value (Infrared)	400	800	4096	19 bit	-
	ADC-Value (Green)	400	800	4096	19 bit	-
	ADC-Value (Ambient)	400	800	4096	19 bit	-
	Heart Rate	10	10	10	0.1 bpm	-
	SpO2	10	10	10	0.1%	-
Opt. Temp. Sensor	Surface Temperature	64	64	64	0.01 °C	±0.2 °C
Pressure Sensor	Air Pressure	120	200	200	0.016 Pa	±8 Pa
	Ambient Temperature	120	200	200	16 bit	±0.03 °C

[90]. The specific sensor we use offers ambient light cancellation up to 200 uA ambient current. Initially, the raw outputs of the ADC (analog-to-digital converter) values for the three LEDs are obtained. We configure the LED current to 20 mA, sample the ADC at 400 Hz with no sample averaging and set the pulse width to 123.8 µs. In the firmware, the heart rate and SpO_2 level are updated with each detected heartbeat directly on the device. Both values can either be streamed at a fixed sample rate of up to 10 Hz or with each new beat. We detect each beat using a falling edge detection in the green led channel. The amplitude of each pulse wave is determined by peak detection before and after the falling edge. To validate that the detected peak forms an actual pulse wave, the relation of the detected characteristic points is tracked. Based on the distribution of these points along all previously detected beats, the new detected beat can be validated. The SpO_2 level is then computed from the amplitude (AC) and the estimated baseline (DC) using the red and IR component. Currently, we do not perform any IMU based motion artifact suppression. This provides a basic computation of the core PPG parameters, with the potential for future improvements.

Optical Temperature Sensor: Melexis MLX90632SLD-DCB-100 [80]. Several variants of the Melexis MLX90632 sensor are available. For OpenEarable 2.0, we have chosen the medical-grade version, which also offers 1.8V logic level compatibility with the MCU, eliminating the need for level shifting. This sensor is factory-calibrated and incorporates an ambient temperature correction feature. Its accuracy varies with the ambient temperature; specifically, it maintains an accuracy of ±0.2°C when measuring object temperatures ranging from 35°C to 42°C within an ambient temperature window of 15°C to 40°C. This precision and range make it well-suited for monitoring typical human body and skin temperatures in indoor environments.

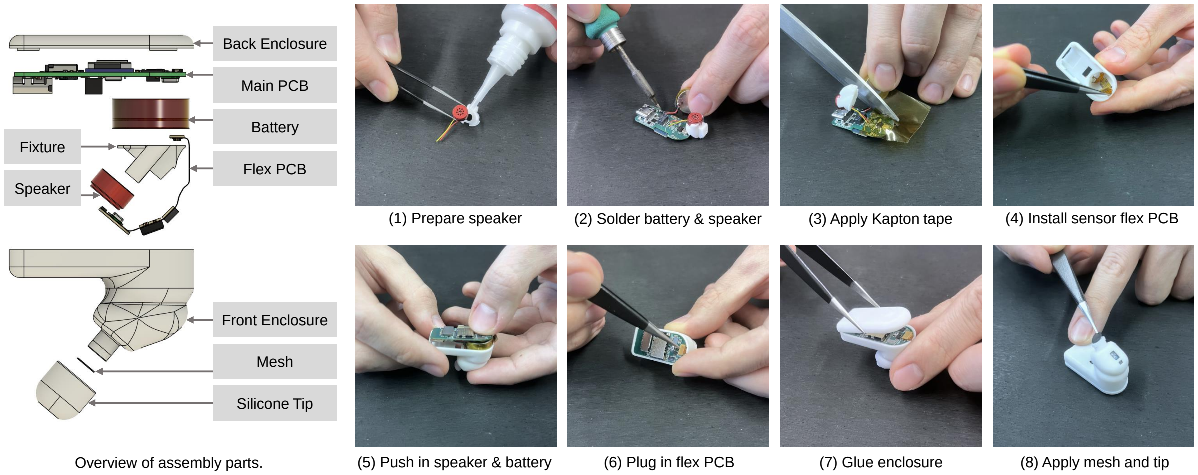


Fig. 5. The picture on the left is an explosion rendering of a right OpenEarable 2.0. It gives an overview of the components required for assembly. The pictures (1) - (6) showcase the assembly steps described in subsubsection 4.2.2.

Pressure Sensor: Bosch BMP388 [23]. The pressure sensor inside OpenEarable 2.0 can measure the pressure inside the ear canal of a wearer which enables different applications [7, 109]. The low power MEMS sensor supports high sampling rates up to 200 Hz. The pressure sensor is partially sealed in the ear canal to increase ear canal deformation pressure changes.

4.2 Mechanical Design and Assembly

For OpenEarable 2.0 the plastic parts were designed hand in hand with the PCBs iterativley to make sure the components fit the enclosure and vice versa. The following sections explaing the manufacturing and assembly process.

4.2.1 3D-printed Parts. For the design of plastic components, we utilize Autodesk Fusion 360 [12], freely available under licenses suitable for educational and personal use. All plastic elements of the OpenEarable 2.0 are crafted for 3D printing using a *Formlabs Form 3+* printer with *White Resin V4*. Alternatively, these components can be ordered from *JLC3DP* using *LEDO 6060 Resin (Natural White)* material. The outer dimensions of OpenEarable 2.0 are 34.6 × 16.7 × 27.0 mm (L × W × H). The design of the enclosure inside the concha is inspired by the *Apple AirPods Pro's* shape and the strategic placement of the different sensors, as described in subsection 3.2. The pulse oximeter and optical temperature sensor are placed in the position typically occupied by the ear detection sensor in *AirPods*, facilitating the use of third-party accessories designed to enhance fit, such as silicone grips. All 3D design files, including the original source files and the exported STLs for 3D printing, are freely available under the MIT license.

4.2.2 Assembly Instructions. The following instructions apply to version 2.0 of OpenEarable. To make this guide future-proof for improvements of OpenEarable 2.0, we ask readers to refer to the project's website for the latest assembly instructions. Before you start, ensure you have the following tools available for assembly: fine-tipped soldering iron and solder, fine-tipped tweezers, wire cutters and strippers, scissors, caliper, viscous superglue (e.g., *Pattex Ultra Gel*), and superglue activator spray. If not ordered online, it is recommended to clean all 3D-printed parts prior to assembly with a rotary tool with sanding tips. For one OpenEarable 2.0 (left or right), you will need the following components, as shown in Figure 5: 1 × rigid main PCB, 1 × flex PCB, 1 × back and 1 × front enclosure, 1 × speaker mount, 1 × 8 mm speaker, 1 × Varta CP1454 A4X coin cell battery (other generations of Varta CP1454 also work but have less capacity), 1 × speaker mesh 7 × 4.2 mm available via AliExpress, and 1 × silicone eartip(s) (*Anker Soundecore* replacement, available in different sizes). A step-by-step video that shows the assembly of OpenEarable 2.0 is available on the project website[1]. A summary of the steps required to assemble OpenEarable 2.0 is given below:

(1) **Prepare speaker:** Trim the speaker cables to *20 mm*. Secure the speaker in its designated fixture using a small amount of superglue, ensuring proper alignment.
(2) **Solder battery and speaker:** Trim the battery cables to *20 mm* (Ground) and *25 mm* (V+). Solder the battery cables and the speaker cables to their respective pads on to the main PCB.
(3) **Apply Kapton tape:** Cover the area on the main PCB where the battery will be placed with Kapton tape. Carefully trim the tape around the edges of the PCB for a clean fit.
(4) **Install sensor flex PCB:** Insert the flex PCB into the front enclosure. Start by positioning the PPG sensor in its designated mount, then push the stiffener toward the ear section. Gently lift and press the temperature sensor into its position. Secure the sensors with small dots of superglue, using activator spray to harden the glue quickly.
(5) **Push in speaker and battery:** Insert the speaker mount, with the attached speaker, into the front enclosure, starting with the side away from the sensors. Ensure a secure fit. Place the battery into its compartment in the front enclosure, with the ground side of the battery facing the main PCB.
(6) **Plug in flex PCB:** Carefully plug the flex PCB into the FPC connector on the main PCB.
(7) **Glue enclosure:** Apply a thin layer of superglue along the edges of the back enclosure. Align it with the front enclosure and press them into place. Allow the glue to fully dry, optionally using activator spray.
(8) **Apply mesh and tip:** Attach the speaker mesh to the front enclosure with a tiny amount of superglue. Finally, add the silicone tip to complete the assembly.

The assembly process is identical for both the left and right ear devices, as the outer shape of OpenEarable 2.0 is mirrored along the vertical axis. The side (left or right) is determined through firmware configuration.

5 SOFTWARE

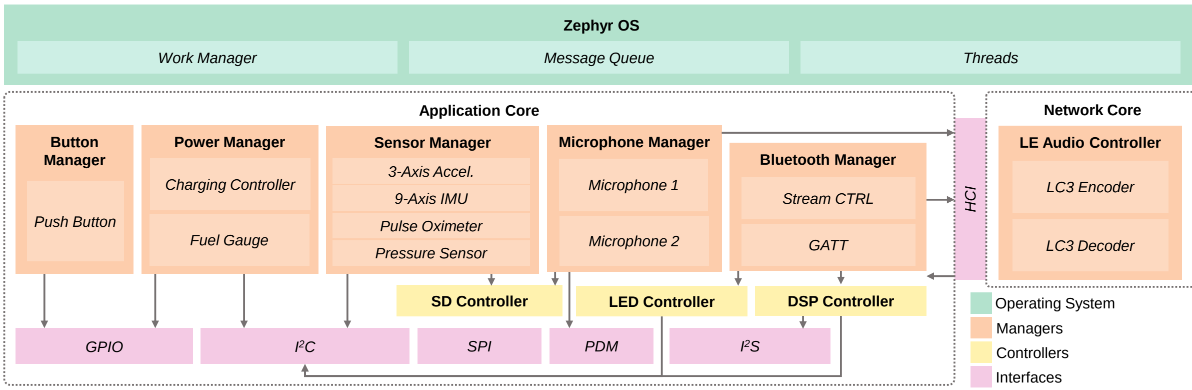
The software ecosystem of OpenEarable 2.0 consists of the firmware running directly on the device and software that can be used for configuring sensors and recording data. The firmware and software (dashboard and mobile app for iOS and Android) are released under MIT license on *GitHub* linked via the project website[1].

5.1 Firmware

The OpenEarable 2.0 firmware is based on the open-source real-time operating system ZephyrOS [130]. By installing the related toolchain in *Visual Studio Code* it is easy to develop and modify OpenEarable 2.0 firmware. A PCB adapter that maps the debugging pin header of OpenEarable 2.0 to a standard 2.54 mm pitch pin header is available on the project's website. The following sections introduce the overall architecture, the states of the push button, and a description of the Bluetooth API. To save energy, the firmware disables sensors that are not used.

5.1.1 Architecture. Figure 6 presents an overview of the OpenEarable 2.0 firmware architecture, structured across three primary layers: the operating system, managers, and controllers, with interfaces facilitating communication with the hardware. The OS layer is based on ZephyrOS [130], which includes a work manager, message queue, and threads ensuring task management and communication. The application core of the nRF5340 runs various managers: the button manager, power manager, and sensor manager handle the device's physical interaction,

[1] https://openearable.com



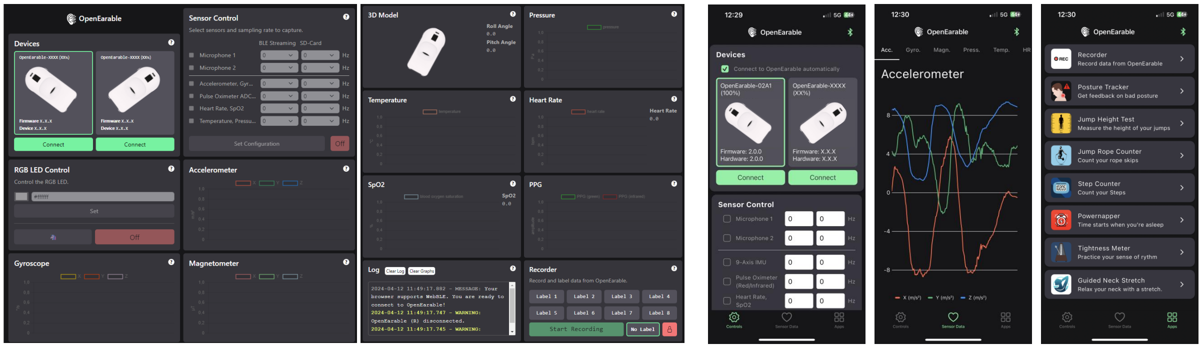
(A) Overview of the *OpenEarable v2* firmware architecture

Fig. 6. The architecture of OpenEarable 2.0 showing the different key components of the firmware.

power and charging regulation, and sensor control respectively, each linked to specific hardware components via interfaces such as GPIO, I²C, and SPI. Similarly, the microphone and Bluetooth managers orchestrate audio input and wireless communication. The network core and application core communicate via HCI/RPMSG. The network core runs the LE Audio Controller which includes the LC3 Encoder, and LC3 Decoder for audio compression and decompression [19]. The layers and their interactions provide a modular approach making the firmware easy to modify for custom applications.

5.1.2 States. The push button of OpenEarable 2.0 is used to control different states of the device. Besides turning the device on and off, it can be used to trigger an action command, to reset the device in DFU mode, to initiate LE Audio pairing, and for pairing a left and right device to act as two earbuds together. The different states are indicated by the RGB LED.

5.1.3 BLE and LE Audio API. OpenEarable 2.0 offers an API via BLE GATT, which stands for Bluetooth Low Energy Generic Attribute Profile [18]. This profile is crucial for structuring data transfer over Bluetooth Low Energy for device-to-device communication. The API allows users to control the sampling rates of the different sensors according to the specification in Table 4. The maximum achievable throughput via BLE across sensors depends on the selected channels to be streamed and the selected sampling rates. Through configuration, data can be streamed via BLE, written to a microSD card, or both. The sampling rates for the microSD card are higher due to its greater throughput capacity. In addition to recording directly on the microSD, the device configuration also allows one microphone to stream via LE Audio, while the other microphone is recorded to the microSD card. The bone conduction microphones can be streamed independently via BLE or recorded to the microSD card. For synchronized recordings, all microphones need to be recorded to the microSD card. In the future, we plan to support stereo air-conducted microphone streaming via LE Audio. The BLE API is compatible with edge-ml.org [118], a no-code framework for embedded machine learning. Additionally, heart rate and blood oxygen saturation data are available through the standardized pulse oximeter BLE GATT profiles. A cross-platform Flutter application (Web, macOS, Windows, Linux, iOS and Android) is introduced in subsection 5.2 and subsection 5.3. To use LE Audio, users connect to OpenEarable 2.0 like they would with regular earphones from their system settings. The device must support LE Audio in order to be compatible with audio streaming of OpenEarable 2.0 (e.g. *Google Pixel 7*). Two OpenEarable 2.0 can be paired as left and right device for stereo LE Audio.



(A) web-based dashboard

(B) mobile cross-platform smartphone app

Fig. 7. (A) An overview of the web-based dashboard including the different configuration panels and real-time data graphs; (B) The sensor configuration page of the mobile app, the real-time data graphs of the mobile app, and different earable "apps" implemented by undergrad students based on the sensors inside OpenEarable 2.0.

5.2 Web Dashboard

The web-based dashboard connects to both a left and right OpenEarable 2.0 device at the same time. It allows users to configure the sampling rates of various sensors for streaming via Bluetooth Low Energy (BLE) or recording to the on-device microSD card. The dashboard displays real-time graphs of the data and features a 3D model of the device that rotates in synchrony with the IMU. Users can control the RGB LED and manage data recording and labeling directly as the data streams to the browser. An event log provides updates on system activities. For the best compatibility it is recommended to use that latest Chrome version (Chromium ≥ 56). Internally, the web dashboard makes use of the OpenEarable 2.0 libraries that encapsulates all functionalities for connection, control and receiving events which can also be used for developing custom applications.

5.3 Mobile App

The mobile app replicates the functionalities of the web dashboard, allowing users to configure various sensors, view real-time data graphs, and a 3D model of the device. It utilizes *Flutter*, a cross-platform framework for iOS and Android smartphone apps [1]. The app also includes several "earable apps" developed by undergraduate students. These applications leverage the sensor streams provided by the Flutter library of OpenEarable 2.0. Example applications include a posture tracker that reminds users to maintain an upright posture and a jump rope counter that tracks the number of jumps. To further understand the opportunities of the OpenEarable framework, an in-depth analysis of 54 undergrad student projects based on the mobile OpenEarable is reported in subsection 6.4. The OpenEarable app is available for download via TestFlight for iOS and as a precompiled APK for Android via the project website[2]. The app is also compatible with macOS, Linux, and Windows.

6 EVALUATION

We evaluated OpenEarable 2.0 by conducting a wearability study to investigate comfort and usability and a sequence of lab experiments to validate and characterise the ability of OpenEarable 2.0 to detect different phenomena. We further demonstrate that users with no prior experience can assemble OpenEarable 2.0 and how undergraduate students make use of earables to create innovative applications. Overall, we address three out of the four overarching evaluation strategies by Ledo et al. [66]: technical performance, demonstration, and usage.

[2]https://openearable.com

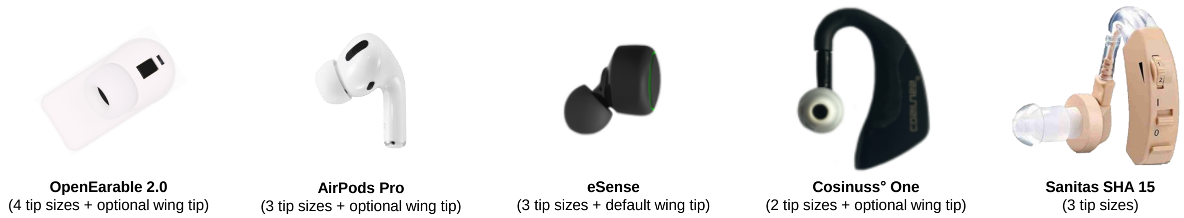


Fig. 8. The different form factors evaluated as part of the wearability study to assess the comfort and wearability of OpenEarable 2.0.

All studies were conducted in accordance with the *Declaration of Helsinki* and within the university's ethics guidelines.

6.1 Wearability Study

We characterise the wearability, comfort, and user preferences of OpenEarable 2.0 and compare it against several commercially available devices using a within-subject design. For comparison, we included the *Apple AirPods Pro*, *Nokia Bell Labs eSense* and *Cosinuss° One*, *Sanitas SHA 15* (see Figure 8). These devices were selected to cover a range of ear form factors and usage scenarios, from those similar to OpenEarable 2.0 to broader variations ranging from mass market products to research devices. We deliberately did not include earlier versions of OpenEarable in the comparison, as OpenEarable 2.0 should replace its former versions.

6.1.1 Procedure. Each participant was instructed to wear each device in both ears continuously during a set of pre-defined activities totaling 30 minutes per device. To focus solely on the physical aspects of wearability and comfort, all devices were turned off during the trial. Each participant chose eartips from a selection (small, medium, and large) that best fit their ear size to ensure both comfort and stability. This procedure was designed to simulate real-world conditions where users select eartips based on personal comfort preferences. In addition, they could use concha wing tips based on their own preference. Each participant was required to perform four activities:

- *Facial movements*: open the mouth wide and raise eyebrows, each done 10 times, and chew gum for one minute.
- *Head movements*: rolling, nodding, and shaking the head, each done 10 times.
- *Body movements*: jumping and bending over, each done 10 times.
- *Physical activities*: walk around the lab's hallway for three minutes, and computer work (self-selected task) for approximately 20 minutes until 30 minutes total wear time had elapsed.

Quantitative subjective data was collected through a questionnaire containing 24 Likert scales in total. Before wearing the devices, the questionnaire assessed visual appeal, style compatibility, perceived quality, and general durability impression. After wearing the devices, the questionnaire assessed comfort, security of fit while worn, impact on physical sensation and movement, discomfort or pain experienced, and ease of learning device attachment and making adjustments for fit. The post-wear questionnaire also included the standardized Comfort Rating Scale (CRS) [63]. Figure 9 details the specific questions asked of participants. In addition, open-ended questions were used to gather qualitative feedback on the overall user experience, aesthetic considerations, and any other observations. Each device was worn for 30 minutes, with 10 minute breaks in between devices. To avoid first-order carryover effects, the order of device was counterbalanced between participants using a balanced Latin square design.

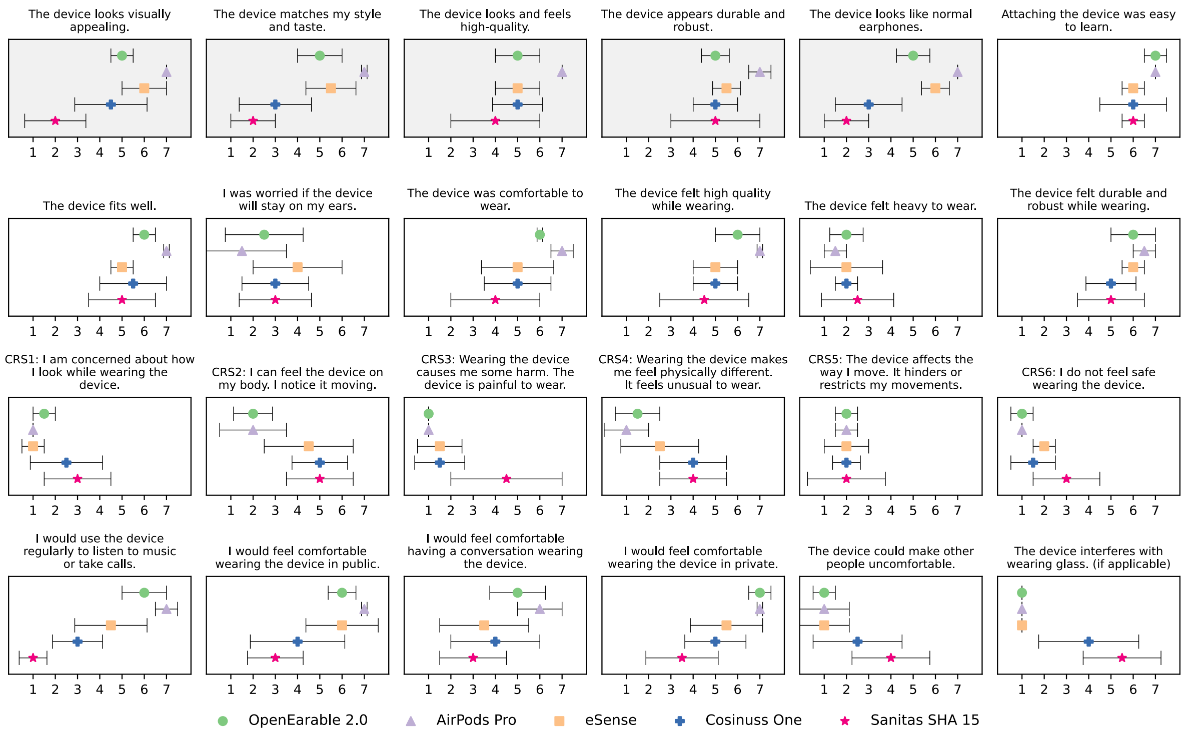


Fig. 9. Results from the wearability study assessing the users perception and comfort of the different earable devices. The graphs with gray background represent items that were queried prior to wearing the device.

6.1.2 Participants. A total of 20 participants were recruited for this study, comprising 13 males and 7 females, with an average age of 31.8 ± 9.3 years. Earphone usage habits varied: 14 participants used earphones daily, 4 regularly (multiple times per week), and 2 occasionally (less than once per week).

6.1.3 Results. The findings are summarized in Figure 9. Statistical analysis was performed using Friedman tests for significant differences per question (alpha = .05) and post-hoc paired Wilcoxon signed-rank tests with Bonferroni correction for inter-device differences (alpha = .05). The results in brackets correspond to the p-value and its effect size of the pairwise comparisons.

Impression and Quality. For visual appeal, OpenEarable 2.0 ranked below *AirPods* (Z=0.0, p = .002) yet above *Sanitas* (Z=23.0, p = .034). Regarding *style matching*, OpenEarable 2.0 differed significantly from *AirPods* (Z=8.0, p = .011) and outperformed *Sanitas* (Z=16.5, p = .025). On *high-quality looks*, OpenEarable 2.0 was rated lower than *AirPods* (Z=0.0, p = .002) and similar to *eSense*, *Cosinuss*, and *Sanitas*. Durability ratings also placed OpenEarable 2.0 below *AirPods* (Z=0.0, p = .008). Finally, on looking *like normal earphones*, OpenEarable 2.0 fell below *AirPods* (Z=4.5, p = .005) but exceeded *Sanitas* (Z=14.0, p = .017). Overall, OpenEarable 2.0 performed comparable to *eSense* and *Cosinuss* in terms of impression and perceived quality.

Attachment and Comfort. Ease-of-attachment for OpenEarable 2.0 was comparable to all other devices (no significant pairwise differences, e.g., vs. *AirPods* (Z=4.0, p > .05). OpenEarable 2.0 *fit* better relative to *Sanitas* (Z=11.0, p = .030) but did not differ from *AirPods*, *eSense*, or *Cosinuss*. OpenEarable 2.0 was more *comfortable*

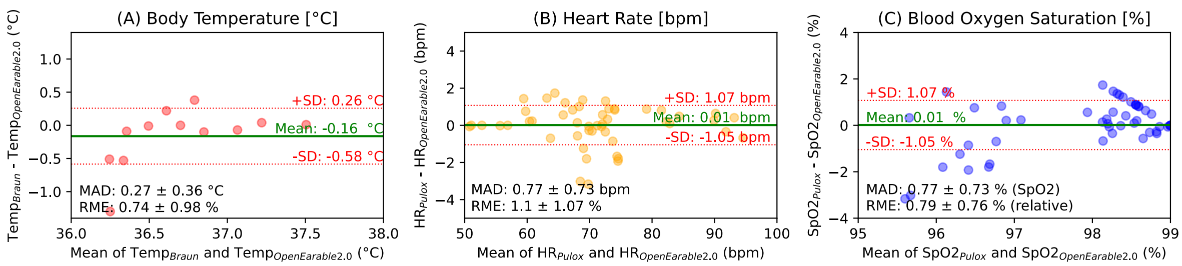


Fig. 10. Bland-Altman plots of the (A) optical temperature sensor performance from 12 participants calculated on 20 minute recording and; (B)-(C) the pulse oximeter performance based on 10 participants with five one minute segments each (heart rate and blood oxygen saturation). MAD = mean absolute difference; RME = relative mean error.

than *eSense* (Z=4.0, p = .020) and *Sanitas* (Z=3.0, p = .005), yet similar to *AirPods* and *Cosinuss*. When worn, OpenEarable 2.0 felt higher-quality than *Sanitas* (Z=8.0, p = .028) but was not different from *AirPods*, *eSense*, or *Cosinuss*. There were no significant *weight* differences to OpenEarable 2.0. Perceived *durability while wearing* and *worries about the device falling off* did not differ for OpenEarable 2.0 vs. any other device. Perceived *movement* was lower for OpenEarable 2.0 than *Sanitas* (Z=11.5, p = .019). OpenEarable 2.0 felt less *painful* than *Sanitas* (Z=5.0, p = .027). No significant differences were found for *movement restrictions* or *safety*. All in-ear devices notably interfered less with wearing glasses.

Social Acceptability. Appearance concerns were lower for OpenEarable 2.0 vs. *Cosinuss* (Z=8.0, p = .045), but not significantly different from *AirPods*, *eSense*, or *Sanitas*. It also felt less *unusual* than *Cosinuss* (Z=8.0, p = .017) or *Sanitas* (Z=3.0, p = .003). On *regular use* intentions, OpenEarable 2.0 outperformed *Cosinuss* (Z=2.5, p = .007) and *Sanitas* (Z=0.0, p = .002). For wearing it *in public*, OpenEarable 2.0 scored higher than *Sanitas* (Z=9.0, p = .008). *Conversation comfort* showed no significant pairwise differences. In *private*, OpenEarable 2.0 was more acceptable than *Sanitas* (Z=3.5, p = .005). Finally, OpenEarable 2.0 was rated less likely to *make others uncomfortable* than *Cosinuss* (Z=5.0, p = .044) and *Sanitas* (Z=6.0, p = .021).

6.1.4 Discussion. OpenEarable 2.0 demonstrated competitive performance compared to both commercial in-ear and around-the-ear devices in terms of impression, quality, attachment, comfort, and social acceptability. This parity suggests that OpenEarable 2.0 has reached a level of wearable experience that aligns with established products in the market, thereby validating its design maturity. While OpenEarable 2.0 did not reach *AirPods* — the highest-scoring device for style and perceived quality — it consistently matched or exceeded the performance of the other options.

Two participants found the 3D-printed nature of the case visually unappealing, while another particularly appreciated this technological style. A participant with small ears expressed concerns about OpenEarable 2.0 potentially falling off, whereas a taller participant noted it felt very stable. Additionally, one participant wished for the device to be less bulky. To improve fit, wing tips from *Apple's AirPods*, which secure the earbud within the concha, can be utilized as they are compatible with the outer dimensions of OpenEarable 2.0. Furthermore, OpenEarable 2.0 supports customized wing tips tailored to the user's ear shape based on ear scans [13, 131].

6.2 Phenomena Validation Studies

To demonstrate and validate the ability of the sensors inside the OpenEarable platform to detect different phenomena we studied them in different sensor validation experiments and compared them to non-ear-based gold-standard sensing.

6.2.1 9-Axis Inertial Measurement Unit. To validate the IMU, we recruited 8 participants (5 male, 3 female, mean age: 27.6 ± 1.65 years) to record activity data under controlled conditions. We captured three minutes of IMU data per participant, divided into three one-minute segments: standing still, walking, and running. The accelerometer, gyroscope, and magnetometer were sampled at 30 Hz from the right ear. We labeled the datasets and imported them into *edge-ml* [118] where they were used to train a random forest classifier. We apply sample-based windowing, specifying window size 30 samples and step size of 30 (no overlap), equivalent to 1 second of data. For feature extraction, we select the "SimpleFeatureExtractor" which is applied to each of the 9-axis (sum, median, mean, std, var, max, absmax, min, absmin). To evaluate the performance we apply 5-fold cross-validation. We achieve an overall F1-score of 97.34% and on a per activity level for standing still 100.00%, walking 96.17%, and running 96.48%. This performance aligns with related work, which reports F1-scores above 95% for similar activity sets [25, 84]. However, as the number of activities increases, performance can drop significantly, reaching as low as 65–70% F1-score when evaluated across the full compendium of physical activities [9].

6.2.2 Optical Temperature Sensor. To validate the optical temperature sensor placed inside the concha, we recruited 12 participants (7 male, 5 female, mean age: 26.0 years). They were invited to our laboratory, where they acclimated for 20 minutes at a room temperature of 25°C, corroborated as sufficient by related research [28]. The temperature at the concha was measured on the right ear using the optical temperature sensor embedded within OpenEarable 2.0. For comparison, the gold-standard tympanic membrane temperature was assessed using a BRAUN ThermoScan 7 [45]. Our analysis revealed a mean absolute difference of 0.27° ± 0.06 °C between the tympanic temperature and that measured by the OpenEarable 2.0 concha sensor, see Figure 10 (A). Subsequently, participants were exposed to outdoor conditions for 20 minutes, during which the mean ambient temperature was 19.38 °C. This exposure led to an observed average temperature drop of -1.67 °C measured by the sensor at the concha with OpenEarable 2.0 compared to -0.25 °C gold-standard tympanic temperature measured by the BRAUN Thermoscan 7. This temperature decrease indicates that the skin temperature at the ear is more susceptible to environmental conditions which must be accounted for when utilizing this sensor. According to the sensor's manufacturer, Melexis, the sensor is calibrated to measure body temperature within an environmental temperature range of -20 to 85 °C with varying accuracy [80]. To increase the robustness against external influence, perhaps machine learning could adjust for ambient conditions using the pressure sensor's thermistor.

The performance found in our study is within the accuracy required for medical applications [127]. Related earable work with the sensor pointing at the tympanic membrane achieved errors of as low as 0.02 ± 0.52 °C, although it required per user adjustments because of ear canal shape differences [17]. A recent comparison study based on the Melexis optical temperature sensor used in OpenEarable 2.0 found that placing the sensor in the concha was more accurate than placing it behind-the-ear [61].

6.2.3 Pulse Oximeter. To validate the pulse oximeter, we recruited 10 participants (7 male, 3 female, mean age: 30.1 ± 5.8 years, Fitzpatrick skin type 1 to 4). Participants arrive at the lab and rest for 20 minutes. We measure the heart rate and blood oxygen saturation for five minutes using the OpenEarable 2.0 pulse oximeter placed inside the concha on the left ear. The raw PPG signal is sampled at 200 Hz (infrared and red). We apply a gold standard pulse oximeter on the finger (*Pulox - PO-200A*) which we record with a smartphone camera to manually extract the heart rate at 1 Hz (1 bpm and 1% resolution).

The results are summarized in Figure 10 (B)-(C). For the collected dataset, the ground truth finger pulse oximeter heart rate's mean across all participants was 70.72 ± 10.59 bpm. Based on OpenEarable 2.0, we find a mean heart rate of 71.34 ± 9.89 bpm across all participants. For evaluation, we split the five minutes per participant into one minute segments and calculate the mean heart rate. The mean absolute difference across all segments was 1.16 ± 1.09 bpm. The relative error per one minute segment (difference divided by ground truth heart rate) was 1.72 ± 1.67%.

For blood oxygen saturation, the ground truth finger pulse oximeter's mean across all participants was 97.92 ± 1.38 %. Based on OpenEarable 2.0, we measured a mean blood oxygen saturation of 97.87 ± 0.89 % across all participants. Similar to the heart rate evaluation, we split the data into one minute segments for more fine granular comparison. The mean absolute difference across all segments was 0.77 ± 0.73 % (SpO2). The relative error per one minute segment (difference divided by ground truth blood oxygen saturation) was 0.79 ± 0.76%.

The heart rate and blood oxygen saturation measurement accuracy of OpenEarable 2.0 is close to gold-standard devices. Medical pulse oximeters are expected to have an accuracy of ±1 bpm for heart rate and ±3% for SpO, as required by standards from the U.S. Food and Drug Administration [47]. In comparison to other sensing principles (ECG, Microphone, Accelerometer), PPG-based heart rate sensing on the ears was found to result in the highest accuracy with the highest robustness [108]. Errors reported in other earable works that placed PPG in the concha reported heart rate errors of as low as -0.19 bpm mean error [41] and -0.03 bpm mean difference [121], which can decrease to a mean absolute error of 1.5 bpm while walking [101]. For SpO_2 related earable works with PPG placed at the concha has reported mean absolute errors between 1% and 2% [41, 72]. To further enhance the accuracy of the ear-based pulse oximeter, we plan to make use of the additional green LED [73] and filter motion artifacts using the 3-axis ear canal accelerometer and 9-axis head inertial measurement unit [115]. The current implementation of the algorithm is basic and will be improved in the future. In addition, the pulse oximeter should be validated in a broader range of blood oxygen saturations and heart rates as well as with darker-skinned individuals [22]. One limitation of our study is that the gold-standard device only has a resolution of ± 1 bpm and 1% for heart rate and SpO2, respectivley.

6.2.4 *Ultrasound-Capable Microphones and Speaker.*

Due to the high expenses and technical complexities involved in setting up a precise testing environment for earphone acoustics, such as the *GRAS 43AG-7 ear & cheek simulator*, we ask readers to refer to the datasheets of the acoustic components used in OpenEarable 2.0. These datasheets ensure experimental reliability without the need for redundant validations (e.g., frequency response). In addition, the microphone has been validated for capturing infrasound audio signals [111].

6.3 Assembly Demonstration

To showcase how easy it is to assemble OpenEarable 2.0, we had a student who recently finished their master's degree in computer science assemble OpenEarable 2.0 for the first time. This assembly was recorded and is available as an instructional video on the project website[3]. The whole assembly took approximately 15 minutes. The student had prior experience with soldering and PCB design. They were permitted to ask questions during assembly to someone familiar with the process, and the manuscript was revised based on these inquiries to better support future users. While familiar with the platform, the student was not involved in the hardware design of OpenEarable 2.0. This demonstrates that individuals with basic technical understanding can readily assemble the device, underscoring OpenEarable 2.0's accessibility for a broader audience.

6.4 Platform Usage Demonstration

From a previous study with undergraduate students it is known that earable prototyping platforms like *eSense* can "create interest in the subject matter and support self-directed learning" [106]. We explored how well undergraduate students could implement earable apps as part of a lecture exercise to further assess how effectively novice developers can leverage earable platforms using the Flutter framework to create applications that demonstrate innovative sensor use. Specifically, this evaluation aimed to understand whether the OpenEarable platform facilitates creative sensor integration and whether it lowers the barrier for entry, enabling new researchers to explore and implement novel functionalities in wearable technology.

[3] https://openearable.com/

6.4.1 Procedure and Apparatus. Students were introduced to Flutter in a three hour long workshop that was independent of any specific earable device platform. They then received an earable device which was shared among groups of three to five students. Each individual student implemented their own earable application and they were tasked with making use of the sensors in an innovative manner as a single page application. Students could select between OpenEarable 1.3 (9-axis IMU, in-ear pressure sensor, in-ear microphone, speaker), eSense (6-axis IMU, microphone, speaker), and a reverse-engineered library implemented by the authors of this paper for discontinued Cosinuss° One (PPG heart rate and SpO_2, 3-axis Accelerometer). There were enough devices for any student to choose any device with any sensor. This evaluation does not use OpenEarable 2.0 but instead a previous version (OpenEarable 1.3) as OpenEarable 2.0 was still under development at the time. The Flutter API the students used is unchanged between OpenEarable 1.3 and OpenEarable 2.0 with the exception of access to more sensors in the latter. The APIs for all three earable platforms are very similar because they wrap the logic for connecting and disconnecting as well as configuring sensor and receiving data. Students used the publicly available documentation of the Flutter libraries and no further instructions were provided. Students worked on the assignment for 40 days and were tasked to implement an innovative use case of earable sensor data.

6.4.2 Measures. Each application was checked to make sure the code compiled and that it worked reasonably well in a sense that the claimed functionality is reproducible, although it may be limited in accuracy. After receiving all completed assignments, we manually grouped the apps, taking inspiration from the sensing and application categories of the earable taxonomy introduced by Röddiger et al. [108]. We measured how innovative the use of sensors were in the student-built applications using three expert evaluators that each rated the earable applications based on a one minute presentation. The raters were a postdoctoral researcher (author of this paper), a university professor (author of this paper), and a research department head from a world-leading engineering and technology company. Each evaluator rated the apps according to the statement *"The earable app utilizes sensors in an innovative manner"* using a five-point Likert scale ranging from "Strongly Disagree" to "Strongly Agree". Raters were instructed to evaluate sensor usage independent of the quality of the presentation. We also counted the numbers of lines in the code implemented by each student to understand the implementation complexity required to realize basic earable sensor use cases.

6.4.3 Results. In total, 54 undergraduate students (39 computer science, 11 business informatics, 1 mechatronics, 3 mechanical engineering) completed the exercise. All apps were successfully confirmed to compile and offer the claimed functionality in a reproducible manner. 28 apps used OpenEarable, 17 eSense, and 9 Cosinuss° One.

Completion rates. All students who registered for the exercise successfully completed it. Students were specifically encouraged to ask questions and reach out if they encountered technical difficulties; only two students did so. One question related to a misunderstanding of IMU functionality, and the other concerned a broken earpiece. This minimal level of inquiries provides evidence that the platforms were easy for students to use.

Sensor Choice. Figure 11 (A) shows the variety of different sensors students chose to user in their applications. Experimentation with sensor combinations, such as pairing heart rate with motion tracking, was rare with only 6 students combining sensors (2 on OpenEarable, 4 on Cosinuss). Instead, we observed that most students favored motion sensors in their applications, likely because of the straightforward cause-effect relationship which made it easy to explore new ideas interactively, with immediate visible feedback from the sensor. Notably, students avoided using the microphone. This could possibly because of the greater complexity involved in processing audio data. For example, in their presentations, many students reported relying on simple threshold-based detection mechanisms.

App Categories. Figure 11 (B) shows a breakdown of the broad range of types of applications students developed for across the different earable platforms. The OpenEarable platform had the widest variety of different application

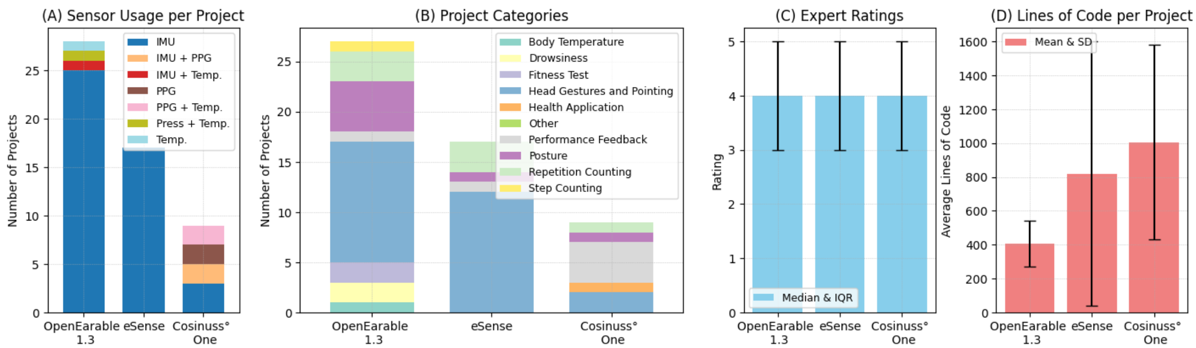


Fig. 11. Comparative analysis of projects utilizing OpenEarable 1.3, eSense, and Cosinuss° One. (A) Distribution of projects based on sensor combinations, showing the variety in sensor integration across platforms. (B) Project Categories: Breakdown of projects by application category, highlighting the diversity in project focus areas. (C) Combined Expert Ratings: Median expert ratings with interquartile range (IQR) across platforms, indicating the perceived effectiveness and utility of each platform for sensor applications. (D) Lines of Code per Project: Average lines of code per project, showcasing development complexity across platforms.

types (N=8) compared with eSense (N=4) and Cosinuss (N=5). The largest group of applications involved leveraging head gestures and pointing (N=26), showcasing relatively simple human-computer interaction techniques. Further analysis shows a wide variety of applications including posture feedback applications (N=7), step counting with heart rate feedback (N=4), running support focused on heart rate tracking (N=3), workout repetition counters for exercises like push-ups including feedback on heart rate during execution (N=5), balance tracking for cyclists (N=1), jump rope counters (N=2), a jump height test (N=1), and yoga posture recognition app with feedback on heart rate and body temperature (N=1). In contrast to earable sensing use cases commonly explored in research, many students focused on implementing games (N=22), which aligns with previous findings that observed a high number of games developed by students using earable prototyping platforms [106]. Additional unique applications included a focus-aware video player (N=1), a drumming rhythm head nodding tracker (N=1), and a weather tracker using the pressure sensor (N=1). Further health-related monitoring included fall detection (N=1) and panic attack detection using the user's heart rate (N=1). Drowsiness detection was implemented via motion and also based on body temperature and heart rate (N=2). One student implemented a napping timer (N=1) and another a fever thermometer (N=1).

Expert Ratings on Innovation Potential. Figure 11 (C) shows the expert ratings based on innovation potential for each earable platform. The overall median was 4 ("Agree") with inter-quartile range (IQR) of 1, a top-two box score of 59% and bottom-two box score of 6%. This indicates that the experts found the applications to exhibit a moderate level of innovation, and while students demonstrated creativity in their sensor applications the perceived innovation was not groundbreaking but leaned toward promising and functional use cases. As can be seen in Figure 11c, there was no difference between earable platforms for level of innovation with all platforms having the same median and IQR.

Implementation Complexity. Analyzing the lines of code revealed large variations between students. The mean number of lines of code per app was 855, with a standard deviation of 679 (median = 637). This suggests that, on average, students were able to implement applications with relatively low effort required. The smallest app had just 266 lines, while the largest comprised 3760 lines. Interestingly, as can be seen in Figure 11 (D), the average lines of code varies for different earable platforms (OpenEarable: 405, eSense: 819, Cosinuss: 1006). This is likely due to the fact students could implement applications into the existing OpenEarable app, whereas the other platforms required more boilerplate code for basic functionality such as connecting the device. This emphasises the advantages of providing open source tooling and platforms to support novice developers.

6.4.4 Discussion. Our analysis demonstrates how an open source earable platform can empower new design participants that have basic technical skills without requiring specialist input. Students were successful in developing earable apps using Flutter libraries to explore innovative use cases and we observed how students combined multiple sensors, creating novel applications that utilized the platform's diverse sensing capabilities. They also incorporated sensors not commonly available on other earable platforms, such as the magnetometer unique to OpenEarable 1.3, to develop creative applications like a stargazing and a street view game that require global orientation.

Our evaluations demonstrate how OpenEarable provides an accessible, easy-to-use entry point into the earable ecosystem, and our analysis of comparable platforms in section 2 shows that OpenEarable 2.0 is the most advanced in terms of sensor integration and capabilities, all while being a fully open source platform. However, it is not clear to what extent OpenEarable 2.0 will enhance the capacity of expert researchers, either making full use of the breadth of sensors currently available in OpenEarable 2.0 or by integrating novel and unique sensing capabilities into the platform.

7 FUTURE WORK AND OPPORTUNITIES

While OpenEarable 2.0 already offers a broad range of sensing capabilities and potential access to 30+ phenomena, there are opportunities to extend the platform even further through additional hardware and software adaptations.

7.1 Hardware Extension and Customization

The design of OpenEarable 2.0 prioritizes flexibility and expansion to cater to a wide range of research interests and custom applications. Central to this adaptability is the 12-pin FPC connector BM46B-12DS (1.8V, 3.3V, GND, GPIO, I²C, PDM, $\text{Speaker}_{\text{OUT}}$, SoftSerial, SoftSPI) and 14-pin header connector on the main PCB (1.8V, 3.3V, GPIO, I²C, PDM, SoftSerial, SoftSPI, SWD). These ports allow for easy customization and extension of the device to meet diverse requirements (e.g., similar to extensions of OpenEarable 1.3 by King et al. [61], Röddiger et al. [111]). In general, other researchers and developers are encouraged to contribute extensions to the *OpenEarable* platform and share them with the community.

7.1.1 Capacitive Sensing Capabilities. A prominent sensing principle on the ears are capacitive electrodes. They can be used for detecting touch and mid-air interaction with an earable [68] or to recognize facial movements [79]. The nRF5340 microcontroller offers native support for capacitive sensing, enabling direct interfacing with capacitive electrodes through its analog pins [93]. In OpenEarable 2.0, the IO1 pin of the 14-pin header connector and the IO4 pin of the 12-pin FPC connector connector are analog. These pins could be used for adding capacitive sensing electrodes to the device with little effort required for additional modifications.

7.1.2 Biopotential Sensing. Another notable area of earable research involves biopotentials to read out brain activity (EEG) [58], eye movements (EOG) [38], facial muscle movements (EMG) [62], and the electric signals of the heart (ECG) [46]. While these signals are promising for many applications, there are currently no standardized hardware components that could be directly integrated into earphones. The internal analog-to-digital converters of the nRF5340 do not have suitable electrical properties for biopotential signals (e.g., impedance, bit resolution) [92]. In addition, the electrodes are challenging to implement because they must be made from special materials [46] or even customized to fit the user's ear [58]. However, the SoftPulse electrodes from Datwyler [51], combined with suitable external evaluation electronics such as an appropriate analog frontend and corresponding amplification circuit make it conceivable to integrate biopotential sensing in the future.

7.2 Software Extension and Customization

The open-source firmware and software provide a flexible foundation for customization and create the opportunity for the community to improve the platform's robustness and capabilities.

7.2.1 Phenomena. OpenEarable 2.0 already includes numerous sensors capable of detecting a broad array of phenomena directly. As illustrated in Figure 2, the potential extends further, allowing for the derivation of additional phenomena. These can be identified by collecting data and, e.g. employing classifiers or regression models for detecting, among others, stress [70], activities [116], energy expenditure [65], navigation [2], posture [117], gait [10], ovulation [71], respiration [112], sleep apnea [125], coughing [107], eating [16], head [44] and hand [55] gestures , emotions [42], user identity based on ear canal sound reflections [43], sleep [125], blood pressure [14], manipulation [129], earable states [64], jaw movements [7], facial expressions [79], tooth brushing [98], silent speech [57], mouth gestures [7], and bruxism [20]. If evaluated as robust, the detection of such phenomena could be integrated directly into the *OpenEarable* software ecosystem. Openly available datasets and further contributions from the community would allow the computation of higher-level phenomena to be directly embedded within the firmware and software which would allow a wider range of people to study these in different contexts and use cases.

An open question that remains is, if automated noise-canceling (ANC) has any detrimental effects on the detection accuracy for some of the described phenomena. Currently, we are not aware of any works that have investigated this issue. In theory, ANC can be supported by the DSPs and microphone configuration inside OpenEarable 2.0.

7.2.2 Sensor Fusion. To further enhance the utility of OpenEarable 2.0, algorithms that combine data from multiple sensors has the potential to improve reliability and device capabilities. For instance, motion artifacts can be filtered out from heart rate data collected via the PPG sensor using the inertial measurement unit [115]. The combination of microphone signals and the pulse oximeter could facilitate blood pressure monitoring [122], while a proximity sensor paired with a microphone inside the ear canal enhances eating detection [16]. The potential to combine multiple sensor also applies to synchronizing sensor signals from both ears. Previous research has demonstrated that merging the PPG signals from both ears can support measuring blood pressure [14] or help determine which side a person is chewing on [99]. The integration of sensors would, therefore, increase data quality and broaden the scope of feasible phenomena.

7.2.3 Applications. A crucial feature of the mobile app and the web dashboard is that they internally leverage standalone libraries for interacting with OpenEarable 2.0. These libraries can be used independently and provide developers with the tools they need to create bespoke applications that meet their own unique research and development needs. The libraries were designed to be easy-to-use, as evidenced by the different earable "apps" in subsection 5.3 which were developed by undergraduate students as part of a lecture assignment.

8 CONCLUSION

OpenEarable 2.0 is a fully open-source platform that integrates a diverse array of sensors in a miniaturized and wearable format and marks a significant step towards advancing and democratizing earable sensing. The modular design and open-source nature of OpenEarable 2.0 provides researchers and developers easy access to advanced ear-based sensing technology that they can modify and extend based on their own needs and requirements. *OpenEarable* provides the foundation for exploring 30+ phenomena which can sensed in, on, or around the ear and the wearability of the device means it can be used to study earable sensing in more ecologically valid settings. The platform has the potential to foster a collaborative earable research community and encourage others to participate in its development, application, and deployment which could lead to consumer and industry applications of earable devices.

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