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A one-size-fits-all earpiece with multiple microphones and drivers for hearing device research

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ABSTRACT

Earpieces that include one or more microphones and drivers are required in many research applications related to hearing devices, however suitable devices are often not readily available. In this contribution, we present the development and evaluation of an earpiece for research on assistive hearing devices and hearables. The earpiece includes two balanced armature drivers as well as four microphones, which are built into a one-size-fits-all acrylic shell. It features custom transducer positioning at different positions inside a vent, as well as a microphone inside the ear canal. We discuss details on the earpiece design, present acoustic measurements and discuss the eligibility for different applications. The earpiece is openly available both in a vented as well as an occluded version.

1 Introduction

All research and development into better assistive hearing devices requires suitable electro-acoustic hardware that can be placed in the ear. Although the specific hardware requirements obviously depend on the application, they generally include the availability of at least one microphone to pick up sound at the ear level, at least one driver to play back sound, and a stable housing that allows testing in real-world settings. However, for many applications no suitable devices are available without larger efforts.

The inavailability of suitable electro-acoustic hardware constitutes a barrier for many researchers, or at least leads to time consuming and tedious work that has to be done in each laboratory independently. Researchers have pursued many different approaches to fulfill their own specific needs, like rewiring commercial hardware [1, 2], manually attaching microphones to earphones [3, 4, 5], or building custom devices from scratch [6]. While manufacturers of headphones or hearing aids may provide special 'dummy' or 'satellite' devices with externally wired transducers, this typically happens inside specific projects and is thus often accessible for selected researchers only. Besides the excessive time spent on the hardware issue, the resulting zoo of custom approaches leads to poor comparability of results from different laboratories.

In this contribution, we present the design and acoustic evaluation of an in-the-ear type earpiece that is suitable for many current research topics related to hearing aids, hear-through headphones and active noise control. The earpiece is made openly available. It builds upon an earlier hand-made prototype presented in [6], which had enabled a number of novel signal processing applications [7, 8, 9, 10, 11]. This first prototype comprised an earmould with a temporarily inserted hand-assembled transducer pack, which led to a large variance between devices and poor mechanical stability. Also, an individual earmould had to be made for each user. To overcome these issues, in the present work we transferred the key aspects of the first prototype into a new earpiece.

The new earpiece contains four microphones, including one in the ear canal, and two Balanced Armature (BA) drivers, which are positioned inside and around and a vent. All transducers are built into a stable one-size-fits-all acrylic shell that fits into about 90% of human ears and sits shallow in the cavum concha. The device can be connected to an arbitrary sound processing platform via a single flexible and sturdy cable. Two versions of the device are considered here: a vented version, and a closed version where the outer part of the vent is completely filled.

The design of the earpiece is described in detail in Sec. 2. Acoustic evaluation measurements and results are described and discussed in Sec. 3, followed by a summary and outlook in Sec. 4.

2 Earpiece Design

In this section, the mechanical and electro-acoustic design of the earpiece is explained. In Sec. 2.1, the general layout is described, and the transducer placement is explained in Sec. 2.2. Details on the form of the shell are presented in Sec. 2.3, followed by details on the selected transducers and microphone preamplifiers in Secs. 2.4 and 2.5, respectively. Note that first, the design of the vented version is outlined, differences in the closed version are described in Sec. 2.6.

2.1 General Layout

The general design of the earpiece is based on the first prototype presented in [6, 7, 12]. It enabled several novel approaches to individualized sound equalization [8, 9], feedback cancellation [10] and electro-acoustic modeling [11]. As discussed above, the first prototype had several issues regarding stability, usability and variation between devices. The aim of the new earpiece is therefore to overcome these issues while maintaining the properties of the first prototype. To this end, in the new earpiece, all components are built into one acrylic shell that can be directly inserted into the ear. Fig. 1 shows the CAD model of the new earpiece. The key features of the earpiece are:

- An in-the-ear fit comparable to an individual earmould.
- A vent containing several transducers, enabling electro-acoustic modelling.
- 3 microphones at the outer surface and the outer end of the vent to enable spatial sound processing.
- An in-ear microphone to monitor the sound pressure in the ear canal and at the eardrum.
- Two BA drivers with separate connections to enable multi-loudspeaker sound processing or two-way playback with a high bandwidth and quality.

The acrylic housing consists of 4 separate parts (see Fig. 1): 1) a shell (gray) 2) a faceplate (violet), which together with the shell forms the outer shape of the earpiece. 3) a vent tube (blue), which extends from the faceplate into the ear canal (some mm past the shell) and houses most transducers. 4) a ring (gray) at the inner end of the vent, which serves as a fixture for the silicone dome and includes the output port and a cerumen filter. All transducers of the earpiece can be connected to a sound processing platform by means of a 1.20 m long flexible 9-pin cable with a Sub-D 9 plug.

2.2 Transducer Placement and Design of the Vent

The schematic placement of the transducers is shown in Fig. 2. As already mentioned, a key feature of the device is the special vent (blue area in Fig. 2) with several transducers coupling into it. This includes

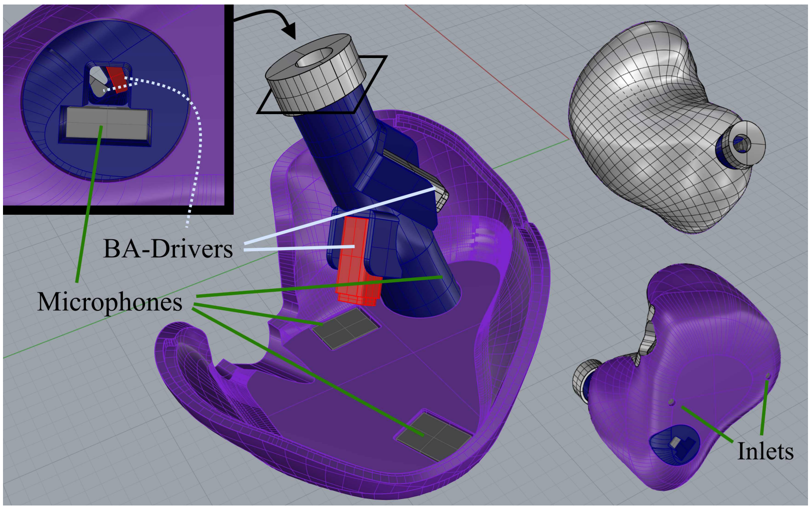

Fig. 1: CAD model of a left earpiece. Center: Interior view with shell removed, right: Inside and outside view of the complete earpiece, top left: View into the vent from the ear canal side, ring removed (plane and viewing direction indicated by the black square and arrow). See text for further details.

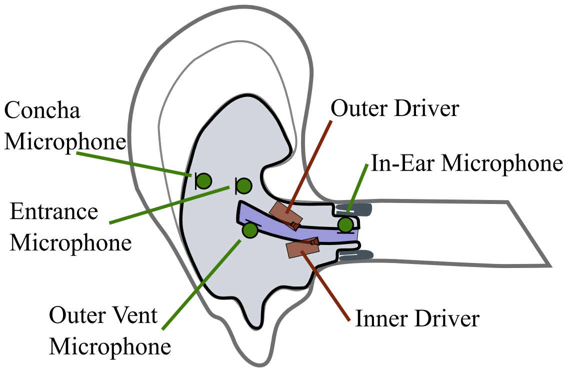

Fig. 2: Schematic layout and placement of the transducers. The shaded blue area denotes the vent, the light gray area the body of the earpiece. The silicone dome in the ear canal is drawn in dark gray.

Fig. 3: Photograph of a right device, outside (left) and inside (right) view. The Entrance and Concha microphones are visible through the transparent acryl, as well as the Outer Vent microphone inside the vent.

microphones at the inner and outer ends (termed *In-Ear* and *Outer Vent* Microphone, respectively), as well as two separate and different BA drivers that couple into the vent at different positions.

The vent has an overall length of 19.2 mm. The microphone inlets are placed close to both ends at its wall, with a 2-3 mm distance to the end to avoid effects of jumps in cross-section [13]. The drivers couple into the vent at 8.1 and 11.4 mm from the inner end (excluding the ring and cerumen filter). They are referred to as *Inner* and *Outer* Driver according to their location. Both BA drivers have a flat outlet, and their ends slightly protrude into the vent while minimizing irregularities of the vent surface (see Figs. 1 and 2).

The vent is primarily included to increase the wearing comfort and to improve the own-voice perception by reducing the occlusion effect [14]. However, a vent unavoidably introduces also some negative acoustic effects [15, 16]: First, it results in a high-pass filtering of sound reproduced by the drivers. Second, it allows low-frequency sound from the outside to leak into the ear canal, which reduces control of the sound generated at the eardrum. This may lead to artifacts due to superposition with the delayed output of the hearing device and may reduce the effectivity of noise reduction algorithms. Third, the acoustic coupling between the drivers and microphones may result in an unstable system and howling sounds. A vent cross-section of ca. 1.5 mm^2 with a roughly quadratic profile that varies slightly over the length was chosen as a compromise between occlusion reduction and the negative effects, particularly sound leakage [14] (c.f. Sec. 3.1).

Two more microphones are mounted on the faceplate of the device in the cavum conchae. One is located in the rear part (termed *Concha* Microphone), the other is located in the frontal part right above the vent, termed *Entrance* Microphone. The distance between both microphones is 11 mm, and their connecting line lies within the horizontal plane for the average ear.

2.3 One-Size-Fits-All Shell

A photograph of the assembled earpiece is shown in Fig. 3. Its outer shape is based on the InEar ProPhile, a commercially available generic fit earphone [17]. Its shape resulted from varying a parametric 3D model to fit inside the maximum percentage of several hundred digitized ear impressions. In a second step, average diameters and angles of ear canals were measured and the innermost part of the device was adapted accordingly. With the resulting shape, a fitting rate of about 90% was achieved.

The innermost part of the vent tube sticks out of the shell and is intended to sit in the outer ear canal, between the first and second bend (see Fig. 3). This part is elliptic (approx. 6x5 mm) and also serves as a mount for a standard silicone dome whose size can be individually selected. The inner side of the vent tube is terminated by a ring that serves as a fixture for the dome (see Fig. 1). A an exchangeable filter (type HF4) is placed in the ring for protection against moisture and cerumen.

For a secure fit, the cable connecting the transducers is lead to the top of and around the ear. This part of the cable is reinforced by a wire and shrink tubing, which enables to bend it to fit the shape of the individual ear (see Fig. 3).

2.4 Transducer Selection

Due to space constraints and the desired output port locations, BA drivers were selected over dynamic drivers. Specifically, a two-way reproduction system is used, comprising a Knowles FK-26768 as a woofer (Outer Driver, see Fig. 1) as well as a Knowles WBFK-30042 as a tweeter (Inner Driver). The tweeter is placed further towards the ear canal to optimize its high-frequency behavior.

For the microphones, a high SNR, stability and a small size is desired. For the in-ear microphone, a hard constraint on the size is imposed since it is placed at the inner surface of the earpiece, i.e., between the first and second bend inside the ear canal. MEMS microphones were selected over electret condenser microphones, which had been utilized in the first prototype [6]. While both feature similar SNRs and comparable sizes, the sensitivity of MEMS depends less on temperature and humidity. Also, the variation between devices is usually smaller than with electret condenser microphones [18]. Specifically, the Knowles SPH1642HT5H-1 was selected, which is 2.65x3.5x1mm in size, features a convenient top port location and provides an SNR of 65 dB. For ANC applications, it is noted that its low-frequency roll off starts at 55 Hz.

2.5 In-Ear Microphone Preamplifiers

To increase the robustness against electromagnetic interferences, crosstalk and to provide line output, microphone preamplifiers were included in the earpiece. They are mounted on a folded flexible Printed Circuit Board (flex-PCB). The transducers are directly mounted on the flex-PCB, such that the assembled electronics can be tested prior to installation into the earpiece. The preamplifiers are supplied by the same contact that provides the microphone supply voltage (3-3.6 V). The four preamplifiers are built as one-stage inverting amplifiers with a gain of 10 dB based on two dual-channel OPA1662-Q1 Op-amp chips.

2.6 Versions

Besides the vented version of the earpiece as described so far, a completely closed version was developed as well. To this end, the vent was completely filled between the coupling point of the outer driver and the outer end of the vent, which implies that the Outer Vent microphone was omitted in the closed version (c.f. Fig. 2). This version may be useful in applications where the drawbacks of a vent outweigh its benefits (c.f. Sec 2.2), e.g., when larger gains in the low-frequency regime or a higher attenuation of external sounds are required.

3 Acoustic Evaluation

Key acoustic parameters were measured for one vented and one closed right-ear device. Assessed parameters include the insertion loss (i.e., the attenuation of external sounds when the device is inserted, see Sec. 3.1), headphone transfer functions (Sec. 3.2), harmonic distortion products and maximum sound pressure (Sec. 3.3), and feedback paths (Sec. 3.4). It should be noted that for the measurements, a development version without the built-in microphone pre-amplifiers was used. Instead, custom microphone pre-amplifiers were connected to the cable. All measurements were conducted at levels that were well within the dynamic range of the utilized microphones and the BA drivers.

For all experiments the earpieces were inserted in a KEMAR 45BB-12 with anthropometric pinnae (G.R.A.S. KB 5000/5001) [19]. This assured a realistic and reproducible coupling to the ear. Depending on the acoustic parameter assessed, the KEMAR was equipped with either low-noise (G.R.A.S. 43BB) or standard IEC711 (G.R.A.S. RA0045) ear simulators, replicating the acoustic properties of an average ear canal and eardrum. The microphones of the ear canal simulator are referred to as (artificial) eardrums in the following.

3.1 Insertion Loss

3.1.1 Methods

The insertion loss, i.e., the attenuation of the transfer function of external sounds to the eardrum by inserting the passive earpiece, was measured on the KEMAR equipped with low-noise ear simulators. The measurements were conducted in an anechoic chamber featuring a 3D array of 94 Genelec 8030 loudspeakers, using overlapping exponential sweeps [20] of 4 s length and a frequency range between 30 Hz and 22.05 kHz, i.e., and half the sampling rate of 44.1 kHz.

Head-Related Transfer Functions (HRTF) of the KEMAR were measured for 47 incidence directions equally distributed on a sphere, once with the ear open (nothing inserted) and 5 times with the passive earpiece reinserted to capture variabilities in the fit. The HRTFs were compensated for residual acoustic reflections by frequency dependent truncation [21] and smoothed over 1/6 octave bands. Then, the average power over directions was calculated and the ratio closed/open ear determined, resulting in the insertion loss for an approximated diffuse field (c.f. [22]).

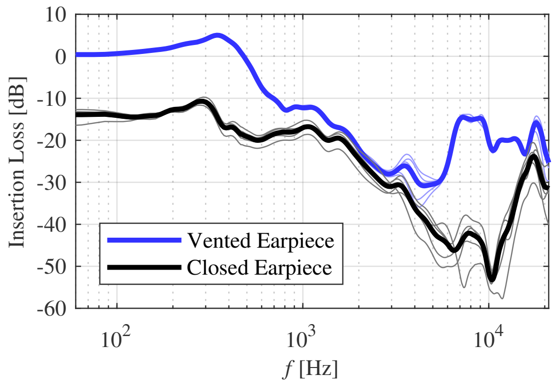

Fig. 4: Insertion loss for approximated diffuse-field incidence with both versions of the earpiece, obtained in a mannequin with anthropometric ears. Thin lines show results for individual reinsertions of the earpiece, thick lines the average.

3.1.2 Results and Discussion

Fig. 4 shows the insertion loss for both versions of the earpiece. The measurement variation between reinsertions is low for both versions, which indicates that a tight fit could be achieved reliably.

In the vented version, external sounds are not attenuated below 500 Hz and the attenuation varies between approx. 10 and 30 dB above 1 kHz. The slight amplification around 350 Hz probably results from a Helmholtz resonance of the residual ear canal and the vent. Generally, this attenuation profile matches typical data for a vent with a 2 mm diameter [14].

In the closed version, an insertion loss of around 15 dB is observed for frequencies below 1 kHz, at higher frequencies it varies between roughly 20 and 40 dB. With this attenuation characteristic, it can be assumed that the influence of direct sound leaking into the ear canal can be neglected in comparison to sound electroacoustically reproduced in a hear-though or hearing aid application. In human subjects, we expect a larger variation particularly in the low frequencies, since the fit is less controlled [5].

3.2 Headphone Transfer Functions

3.2.1 Methods

The Headphone Transfer Function (HpTF), i.e. the pressure generated at the artificial eardrum depending on the driving voltage and frequency was measured for both drivers independently in the KEMAR equipped with the standard ear simulators. The measurements were performed using an Audio Precision APx525 analyzer and its software (APx500 suite) at a sampling rate of 192 kHz. An exponential sweep covering the range between 30 Hz and 30 kHz with an RMS voltage of 400 mV was used. The BA drivers were fed through a Lake People G-103P amplifier adjusted to 0 dB gain.

3.2.2 Results and Discussion

Fig. 5 shows the HpTFs for both versions of the earpiece and for both drivers. Differences are evident both between the closed and vented versions as well as between the driver positions/types.

Independent of the driver, the most pronounced difference between the vented and closed version is the low-frequency response. Whereas the low-frequency response is flat in the closed earpiece, for the vented earpiece a bass roll-off with a cut-off frequency of about 300 Hz is observed. This is caused by a reduced acoustic impedance of the unsealed ear canal, which is unavoidable whenever a vent is present. It should be noted, however, that the cut-off frequency for the playback lies around 200 Hz below the cut-off frequency for the attenuation of external sounds (c.f. Fig. 4). In addition, in a wide frequency range between 800 Hz and ca. 6 kHz, the response is between 5 and 10 dB higher in the closed earpiece as compared to the vented earpiece.

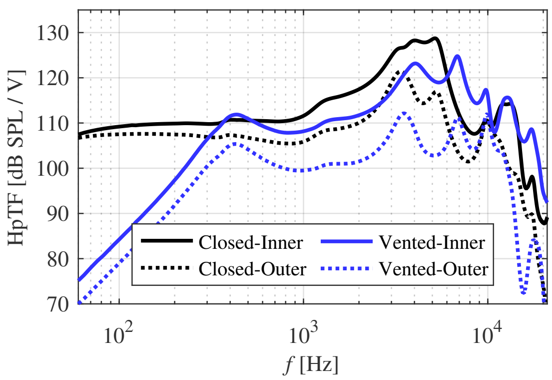

Fig. 5: Headphone Transfer Functions (HpTFs) for both versions of the earpiece (indicated by the color), and for the inner (solid lines) and outer (dashed lines) driver position, respectively.

Between both drivers, a general offset in sensitivity of 5-10 dB is evident, where the inner driver has the larger sensitivity. This is mostly caused by selecting different types of drivers featuring different impedances at both positions (c.f. Sec. 2.4), which has been verified by individual characterization of the driver types. Moreover, their high-frequency responses vary: Whereas the inner driver features a broad peak between 3 and 6 kHz and another peak at about 13 kHz, the response of the outer driver is rather flat below 10 kHz (particularly in the vented earpiece), with only some smaller peaks. Furthermore, the responses of the individual drivers vary between the earpiece versions.

These data verify that the drivers have largely complementary characteristics, as intended by design. High frequencies can better be reproduced by the inner driver, whereas the outer driver mainly supports sound reproduction up to about 10 kHz. The small broadband difference in sensitivity is not expected to be a problem with suitable electronic circuitry.

In both versions of the earpiece, a high reproduction bandwidth far beyond 10 kHz can be achieved, whereas the low-frequency behavior depends on the version.

3.3 Distortions Products and Maximum SPL

3.3.1 Methods

Using the same setup and equipment as for the HpTF measurements (see previous section), the Total Harmonic Distortion (THD) generated by the drivers was characterized as a function of the produced sound pressure level (SPL) at the artificial eardrum. To this end, a 1 kHz sine tone was played and the driving voltage was varied between -10 and 10 dBV. The ratio between harmonic distortion components and the playback frequency was determined using the APx525 analyser's software.

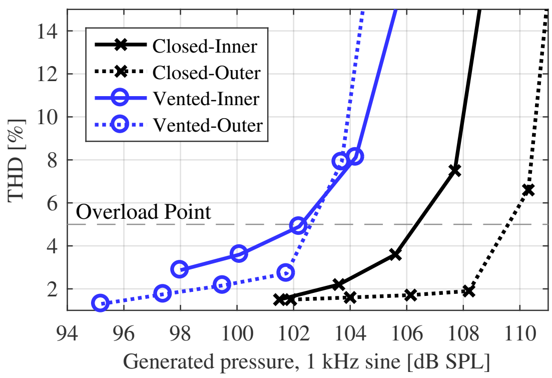

Fig. 6: Total Harmonic Distortion (THD) ratio as a function of SPL generated at 1 kHz for both versions of the earpiece (indicated by the color), and for the inner (solid lines) and outer (dashed lines) driver, respectively.

3.3.2 Results and Discussion

Fig. 6 shows the THD ratios as a function of the produced SPL for both drivers and earpiece versions. As expected, the THD ratios gradually increase with increasing SPL up to the saturation point of the drivers, above which the THD increases rapidly. This point lies at approx. 5% THD and characterizes the maximum SPL that can be generated with a particular driver and earpiece version (dashed horizontal line in Fig. 6).

With the vented earpiece, about 103 dB SPL can be generated, independent of the driver. With the closed earpiece, about 109 and 107 dB SPL can be reproduced with the outer and inner driver, respectively. By combining the output of both drivers, a 6 dB increase can, in principle, be achieved. In summary, the achievable SPLs should be sufficient for most applications with normal-hearing or mildly hearing-impaired users. At more moderate SPLs, the THD ratios lie in the typical range for BA drivers.

3.4 Feedback Paths

3.4.1 Methods

The acoustic feedback paths, i.e., the transfer functions between the drivers and the microphones of the earpiece, were measured while the earpiece was inserted into the KEMAR equipped with low-noise ear simulators. Five repetitions with reinserting the device were assessed to capture variabilities in the fit. An exponential sweep with ca. 75 mV RMS, 4 s length and a frequency range between 30 Hz and 22.05 kHz, i.e., half the sampling rate of 44.1 kHz, was used.

3.4.2 Results and Discussion

Fig. 7 shows the amplitude of the obtained feedback paths between the inner driver and all microphones for both versions of the earpiece. The feedback paths for the outer driver are very similar. For comparison, the HpTFs to the artificial eardrum (measured together with the feedback paths) are shown. All feedback paths are well reproducible, especially in the vented earpiece.

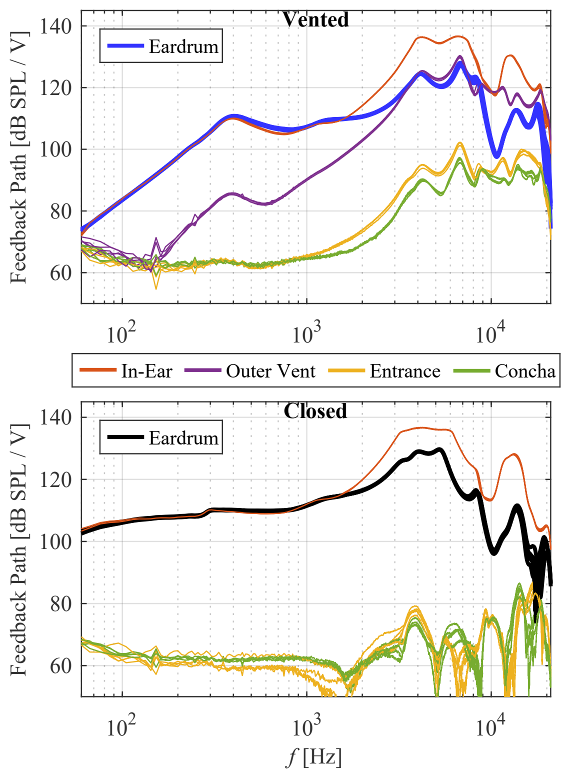

Fig. 7: Feedback paths between the inner driver and the device's microphones (as indicated by the color). Upper panel: results for the vented earpiece, lower panel: closed earpiece. Transfer functions to the artificial eardrums (HpTF) for comparison (colors consistent with previous figures), individual lines show results for 5 reinsertions.

Such reproducibility is typical for in-ear devices as compared to behind-the-ear devices [23].

For the vented earpiece, the feedback paths to the microphones in the vent deviate significantly from the feedback paths to the microphones mounted at the faceplate. Especially the broadband 30 dB difference between the feedback paths to the Outer Vent and the Entrance microphone is striking, given the very small distance between both microphones (see Fig 3). One possible explanation is that the vent emits sound to the outside in a very directional manner. On the other hand, the feedback paths are very similar for the Entrance and Concha microphones. For these microphones, the attenuation compared to the HpTF to the eardrum is larger than 20 dB for frequencies < 8 kHz. Given these data, it seems appropriate to utilize only the Entrance and Concha microphones for picking up sound for processing. Future research is required to evaluate whether multi-microphone feedback suppression techniques would also benefit from using the Outer Vent and/or In-Ear microphones, as already shown in the first prototype [7, 10].

For the closed earpiece, the feedback paths are generally smaller in amplitude than for the vented earpiece. Note that in the closed earpiece, there is no Outer Vent microphone. The attenuation compared to the HpTF to the eardrum is larger than 40 dB for frequencies $<$ 8 kHz, and larger than 20 dB below 15 kHz. Thus, we hardly expect problems with feedback for the closed earpiece when using moderate gains.

Independent of the version of the earpiece, the feedback path to the In-Ear microphone is almost identical to the HpTF to the eardrum for frequencies < 1.5 kHz. At higher frequencies, the amplitude is up to approx. 20 dB larger at this microphone than at the eardrum. A similar relative transfer function between both locations was observed also for external sound sources.

4 Summary and Outlook

We presented the design and acoustic evaluation of an earpiece with multiple microphones and drivers that can serve as ear-level hardware for research hearing devices. It contains four microphones and two drivers, which opens up numerous possibilities for signal processing. The earpiece is made up from a one-size-fits-all generic shell that sits shallow and firm in the cavum conchae.

In summary, the acoustic measurements showed that the features intended with the design were largely achieved. That is, the achieved bandwidth, maximum sound pressure level, attenuation characteristics and feedback paths show that the earpiece is suited to construct and study high-fidelity hearing devices for a range of applications. The vented and the closed versions have many comparable, but also complementary properties, particularly regarding leakage of external sounds and the low-frequency behavior.

Future work includes evaluating algorithms for sound pressure equalization, feedback cancellation and active noise/occlusion control on the new earpiece, in particular approaches that worked well on our first prototype [6, 7, 8, 9, 10, 11]. There, the two versions of the earpiece allow a direct comparison between open and closed fits without changing any other parameters in a range of research questions.

Availability

Both versions of the earpiece are commercially available from InEar GmbH, Dieburg, Germany. More information can be found at `https://www.hoertech.de/en/f-e-products/transparent-earpiece-2.html`.

Acknowledgement

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