

On the limitations of sound localization with hearing devices

Florian Denk,^{a)} Stephan D. Ewert, and Birger Kollmeier

Medizinische Physik and Cluster of Excellence "Hearing4all," Universität Oldenburg, K pkersweg 74, 26129 Oldenburg, Germany

(Received 2 April 2019; revised 26 August 2019; accepted 28 August 2019; published online 25 September 2019)

Limited abilities to localize sound sources and other reduced spatial hearing capabilities remain a largely unsolved issue in hearing devices like hearing aids or hear-through headphones. Hence, the impact of the microphone location, signal bandwidth, different equalization approaches, as well as processing delays in superposition with direct sound leaking through a vent was addressed in this study. A localization experiment was performed with normal-hearing subjects using individual binaural synthesis to separately assess the above-mentioned potential limiting issues for localization in the horizontal and vertical plane with linear hearing devices. To this end, listening through hearing devices was simulated utilizing transfer functions for six different microphone locations, measured both individually and on a dummy head. Results show that the microphone location is the governing factor for localization abilities with linear hearing devices, and non-optimal microphone locations have a disruptive influence on localization in the vertical domain, and an effect on lateral sound localization. Processing delays cause additional detrimental effects for lateral sound localization; and diffuse-field equalization to the open-ear response leads to better localization performance than free-field equalization. Stimuli derived from dummy head measurements are unsuited for evaluating individual localization abilities with a hearing device.

  2019 Acoustical Society of America. <https://doi.org/10.1121/1.5126521>

[VB]

Pages: 1732–1744

I. INTRODUCTION

The limited ability to localize sound sources remains an unsolved issue in hearing aids and related devices for normal-hearing users. That is, hearing aids often impose additional sound localization difficulties for hearing impaired subjects, or in the best case provide no benefit in this respect (Akeroyd and Whitmer, 2016; Kollmeier and Kiessling, 2018). An impairment of spatial hearing due to wearing a hearing device is even more critical for the acceptance of devices targeted to normal-hearing users, like hear-through headphones or electronic hearing protectors (H rm  et al., 2004; Hoffmann et al., 2014; Killion et al., 2011; Marentakis and Liepins, 2014; Tikander, 2009).

The limitation of sound localization abilities with hearing devices results from an insufficient conservation of directional cues that are usually created by sound transmission through the open ear. These cues are described by the Head-Related Transfer Function (HRTF) and include both interaural time (ITD) and interaural level (ILD) cues as well as monaural spectral cues. Whereas the interaural cues are mostly exploited for lateral (i.e., left-right) localization, monaural spectral cues as well as time-variation of binaural cues originating from head movements are exploited to determine the vertical position of a sound source, which includes the discrimination of the front and rear hemisphere in the horizontal plane (Blauert, 1997). A principal limitation on how well directional cues can be conserved is imposed by the directional information captured by the device microphone(s)

depending on their location. Other potential sources of inaccuracies are the algorithms operating on the device, the processing delay, and the reproduction bandwidth (Akeroyd and Whitmer, 2016; Byrne and Noble, 1998; Denk et al., 2018b).

The detrimental effects of hearing devices on sound localization have been assessed mostly by having subjects localize free-field sound sources while wearing hearing devices (Best et al., 2010; Brungart et al., 2003; Brungart et al., 2007; Byrne and Noble, 1998; D'Angelo et al., 2001; Hoffmann et al., 2014; Van den Bogaert et al., 2006; Van den Bogaert et al., 2011). While very realistic results can be obtained in such experiments, it is hard to determine at what stage which cue is distorted and how this affects sound localization. In the present work, we used individual binaural synthesis (M ller, 1992) to separate and quantify the influence of the separate stages in a hearing device processing chain on sound localization. To this end, stimuli that resembled listening through simulated hearing devices, where the separate (detrimental) aspects could be turned on and off freely, were presented over headphones. We thereby made use of HRTFs that have been measured at the microphone locations of several device styles in individual subjects (Denk et al., 2018a). Normal-hearing subjects were employed here to assess the principal limitations on sound localization when listening with hearing devices, independent on additional difficulties through a hearing impairment (Noble et al., 1997). Localization performance was assessed for the full horizontal and median planes in separate experiments to assess effects on both lateral and vertical sound localization.

The first stage in the hearing device where directional cues can be distorted is the sound pickup at a non-optimal microphone location. To study the isolated effect of the

^{a)}Electronic mail: florian.denk@uni-oldenburg.de

microphone location, stimuli were convolved with the individual HRTF to the hearing device microphone, which was individually equalized against the HRTF to the eardrum of the open ear (open-ear HRTF). This is the best possible listening condition based on the hearing device microphone signal. The tested microphone locations covered the whole range of devices in use today, from optimum locations in the ear canal over various locations in the cavum conchae to a microphone behind the ear. The impact of the microphone location in isolation has been previously studied in the context of vertical localization by means of computational models (Denk *et al.*, 2018b; Durin *et al.*, 2014). There, a strong detrimental effect of the microphone position was observed, which, however, has not yet been verified in listening tests. In free-field localization experiments with hearing aids, only small effects of the microphone location have been found (Best *et al.*, 2010; Jensen *et al.*, 2013; Van den Bogaert *et al.*, 2011; Brungart *et al.*, 2003). To assess the influence of a restricted bandwidth as in many concurrent devices, the equalized HRTFs were also low-pass filtered at 8 kHz. For vertical localization, previous model studies predicted a generally poorer performance with low-pass stimuli, and smaller differences between microphone locations (Durin *et al.*, 2014). Furthermore, we compared equalization to the open-ear response for frontal against diffuse-field incidence. While our previous work demonstrated that diffuse-field equalization minimizes the spectral differences against the open-ear HRTF (Denk *et al.*, 2018a), the impact on localization is unclear.

The effect of a processing delay was assessed by simulating the superposition of the hearing device output and an acoustic leakage component that directly enters the ear canal through a vent. We chose a delay of 6 ms, which is in the typical range for relevant hearing devices and causes a perceivable disturbance (Groth and Søndergaard, 2004; Stone *et al.*, 2008). Since the virtual hearing devices were targeted for normal-hearing subjects, the device output was filtered in a way that the superposition of both sound components approximates the open-ear HRTF (Denk *et al.*, 2018d). Note that this condition does not include compression or synchronization artifacts, i.e., the same constant delay was present at both sides without variations. Also, the processing is restricted to a linear filtering operation. While this is realistic for many devices targeted to normal-hearing users, this condition does not account for the effect of the non-linear processing in most modern hearing aids.

Furthermore, localization performance was assessed where the appropriate HRTFs were measured on a KEMAR to study to what extent such psychophysical studies require the use of individually measured hearing device HRTFs. To the authors' best knowledge, this aspect has not been studied before.

For the isolated effect of the microphone location, we expect an impairment of localization mostly in the vertical domain, since positioning the microphone away from the ear canal results most prominently in a bias of spectral directional cues (Denk *et al.*, 2018b; Durin *et al.*, 2014). Based on previous data discussed above (Best *et al.*, 2010; Van den Bogaert *et al.*, 2011), we expect no influence of the microphone location on lateral localization. Given that the processing delay could potentially disrupt ITD cues, we expect a

detrimental effect on lateral localization, but no detrimental effect for vertical sound localization.

II. METHODS

A. Outline

The subjects localized sound sources while sitting inside an anechoic chamber with a visible array of loudspeakers at the positions of the sound sources (see Fig. 1). The main part of the experiment included stimuli presented over headphones after convolution with appropriate HRTFs, referred to as virtual stimuli. These stimuli simulated listening through idealized linear hearing devices, where the effects of microphone position, bandwidth, a vent, and processing delays were assessed. For training purposes, the subjects also localized free-field stimuli presented over the loudspeakers. Individual HRTFs had been measured using the very loudspeaker system utilized for free-field sound presentation (Denk *et al.*, 2018a). When conducting the virtual localization trials, the subjects were not informed that only the headphones were used for playback.

Localization performance in the median and horizontal plane was assessed in separate experiments. In the median plane, elevations between -30° and 90° with a uniform spacing of 15° both in the front and rear hemisphere were used, adding up to 17 incidence directions. The horizontal plane experiment included 24 directions with a uniform spacing of 15° .

B. Apparatus

The study was conducted in the Oldenburg VR-Lab, which is an anechoic chamber featuring a 94 channel three-dimensional array of Genelec 8030 loudspeakers with a distance varying between 2.5 and 3 m from the center point. Figure 1 shows a subject seated in the chamber while conducting the experiment. Thirty-nine loudspeakers were utilized for free-field sound presentation and uniquely labelled; the loudspeakers directly in front and behind the subject were included in both the horizontal and median

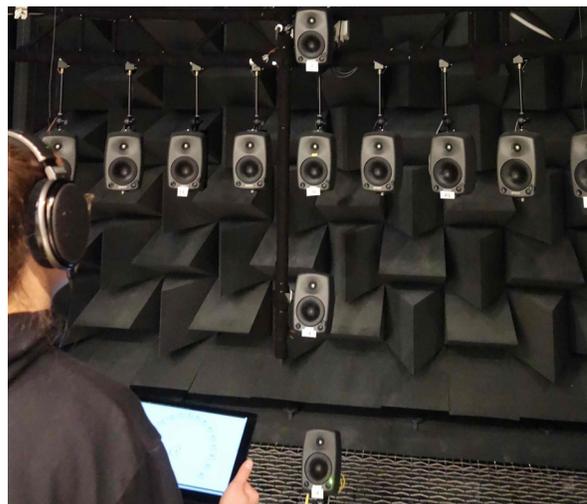


FIG. 1. (Color online) Subject participating in the experiment. The loudspeakers are labelled using a white sticker at the bottom. Note that in the horizontal plane, only every other installed loudspeaker (with white label) is used.

plane. The loudspeakers were individually equalized such that their pseudo-anechoic frequency response (reflections from the other loudspeakers windowed out; [Denk et al., 2018c](#)) was flat between 80 Hz and 18 kHz.

Virtual stimuli were presented from open-coupling Sennheiser HD650 headphones, driven by a Lake People G-103P amplifier. The headphones were individually equalized to produce a flat frequency response at the eardrum to avoid a double influence of the ear canal, based on individual Headphone Transfer Function (HpTF) measurements that had been conducted with the HRTF measurements. To this end, the HpTF to the eardrum was estimated by transforming the HpTF measured at the blocked ear canal entrance by the transfer function between that location and the eardrum obtained in free-field measurements, assuming that the headphones are free-field equivalent coupling ([Møller et al., 1995](#)).

The subjects indicated the perceived incidence direction by clicking buttons on a Graphical User Interface (GUI) that depicted the labelled loudspeakers, which means the responses were restricted to the actual loudspeaker locations. Different GUIs were utilized for the separate horizontal and median plane localization tasks. The GUI was displayed on a handheld tablet with a 10 in. touchscreen (see in Fig. 1, median plane GUI displayed). After clicking a response button and a pause that lasted randomly between 1.5 and 2.5 s, the next stimulus was presented automatically. By means of a headtracker (Pohlemus Patriot) we ensured that before stimulus playback the subject's head was centered in the loudspeaker array and oriented towards the front. If the position exceeded the tolerance of 5° or 5 cm in either degree of freedom, a message was displayed, and the experiment halted until the position was restored.

C. Listeners and individual HRTFs

Eleven normal-hearing subjects (including one of the authors, age 29.8 ± 4.6 , five females) participated in the study after giving written informed consent. HRTFs had been measured individually for all subjects at the eardrum and locations in the ear corresponding to microphone locations of a range of hearing devices, including the blocked ear canal entrance. Also, the individual HpTF had been measured at the blocked ear canal entrance. The dataset is publicly available ([Denk et al., 2018a](#)).

HRTFs had been measured using the installed loudspeaker system for all directions of interest except those at elevations $\pm 15^\circ$, $+45^\circ$, and $+75^\circ$ in the median plane. There, HRTFs were computed by linear interpolation in magnitude and phase separately between the next neighbor locations in the median plane ([Nishino et al., 1999](#)). For the locations at $\pm 15^\circ$, the symmetric distance to the next neighbors was 5° (interpolation between the HRTFs at $\pm 10^\circ$ and $\pm 20^\circ$), for the others 15° (interpolation between 30° and 60° for 45°, and between 60° and 90° for 75°). In a model evaluation, the directional resolution of the measurements was proven to be sufficient ([Denk et al., 2018b](#)).

D. Listening conditions and stimuli

Linear hearing devices were simulated aiming for acoustic transparency, i.e., adjusted to approximate the open-ear HRTF as well as possible. A subset of six hearing device microphone locations from the available database was used, for more details and an image of the microphone locations in the ear, the reader is referred to [Denk et al. \(2018a\)](#). The order below reflects their approximate distance from the eardrum.

- ECEbl: Blocked ear canal entrance. Ideal recording point, equivalent to microphones of in-the-canal devices. This point is also referred to as the reference location in the following.
- InsertHP: microphones placed on small insert headphones (Sennheiser CX200).
- ITEind: microphones placed on an earmould filling the concha bottom completely, one near the ear canal entrance (ITEind_Entr), and one in the rear part of the cavum conchae (ITEind_Concha).
- ITEgen: microphone placed on a generic ITE device, near the ear canal entrance (ITEgen_Entr in the database).
- BTE: microphone on a Behind-The-Ear hearing aid dummy. For this study, we chose the middle microphone (BTE_mid) from the database.

Different processing schemes resembling different listening conditions based on the hearing device HRTFs were employed. The basic scheme for the calculations is shown in Fig. 2, and the individual processing schemes are described in detail below:

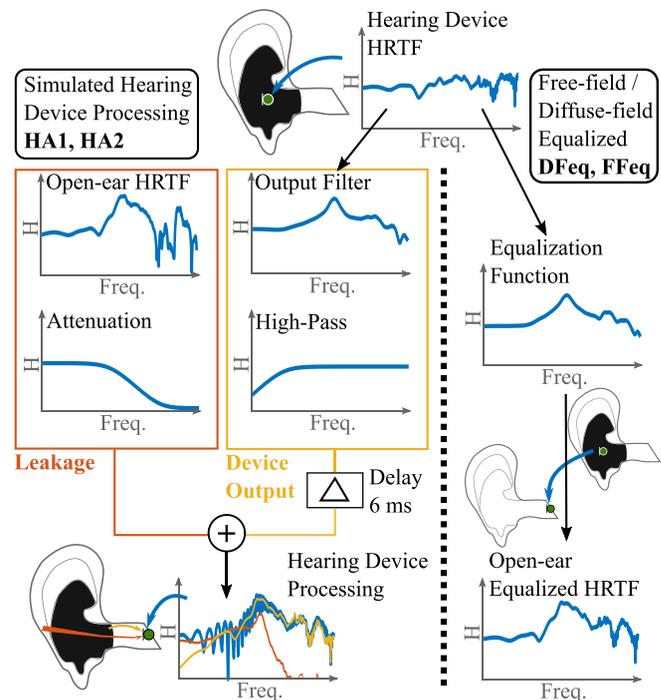


FIG. 2. (Color online) Signal flow for equalizing the hearing device HRTFs (right side, processing schemes DFeq and FFeq, curves show DFeq) and simulating linear hearing device processing with delay (left, processing schemes HA1 and HA2, curves show HA2).

- DFeq: Diffuse-field equalization against the eardrum-HRTF. The HRTF at the appropriate microphone location was transformed for each subject by the individual diffuse-field transfer function between the appropriate microphone location and the eardrum (cf. individual diffuse-field Target Response Correction Function in [Denk et al. \(2018a\)](#)).
- DFeq-LP: As DFeq, but with a low-pass filter at 8 kHz (8th order Butterworth) applied to the resulting HRTF.
- FFeq: As DFeq, but utilizing the appropriate free-field correction function, i.e., the transfer function between the appropriate microphone location and the eardrum for frontal incidence.
- HA1: Simulated hearing device processing with a leakage component: The hearing device output is adapted such that the diffuse-field equalized HRTF is approximated; see [Fig. 2](#). The sound reaching the eardrum includes a leakage component, simulated by the individual open-ear HRTF filtered with a high-shelving filter (2nd order, cut-off frequency 2.5 kHz, high-frequency attenuation 25 dB). An output filter for the hearing device was calculated using a least-squares design that exploits knowledge of the leakage component, as proposed in [Denk et al. \(2018d\)](#). The design method results in a reduction of hearing device output in frequency regions where the direct sound component is sufficient to produce the desired frequency response at the eardrum, leading to a reduction of comb filter effects. The hearing device output had a delay of 6 ms with respect to the direct sound component, and included a second-order high-pass filter (2nd order Butterworth) at 500 Hz to account for the vent effect.
- HA2: Simulated alternative hearing aid processing with a leakage component: The same acoustic parameters and filter design method as in HA1, but where the leakage component was not considered in the output filter design. In consequence, the leakage component and the device output superimpose in a broader frequency range and generate more comb filter artifacts.

Whereas, generally, individual HRTFs were employed to generate the stimuli, the diffuse-field equalized hearing device HRTFs were also computed with HRTFs measured in a KEMAR ear at the appropriate microphone locations. They are implemented to assess the influence of using KEMAR-derived HRTFs for evaluating sound localization with such devices as compared to individual HRTFs. For simplicity, they are treated as further processing schemes:

- DFeq-KEMAR: As DFeq, but taking the HRTF of the KEMAR mannequin.
- DFeq-LP-KEMAR: As DFeq-LP, but taking the HRTF of the KEMAR mannequin.

The conditions included in the localization experiments consist of combinations of microphone locations and processing schemes as listed in [Table I](#). While localization was tested for all microphone locations in the DFeq processing, the different processing schemes were tested only with a subset of microphone locations, namely, ECEbl (perfect spatial cues), ITEind_Entr (disturbed cues), and BTE (highly

disturbed cues, no pinna effects). The effect of low-pass filtering the stimulus was only tested in the median plane experiment, since no effect on lateral localization is expected. Note that for the ECEbl location, diffuse-field and free-field equalization functions are identical ([Denk et al., 2018a](#)), and thus the results of ECEbl-DFeq were copied to ECEbl-FFeq for clarity.

Every incidence direction was presented once to each subject, except in the ECEbl-DFeq (reference) condition. There, each incidence direction was repeated three times to provide a larger portion of well-localizable stimuli, as well as being able to assess the performance with the same accuracy as in the training sessions (see [Sec. IIE](#)). The number of stimuli amount to 456 for the horizontal plane experiment and 476 for the median plane experiment. While the horizontal plane includes more directions, a higher number of conditions was included in the median plane experiment (leading to 28 presentations of each direction) as compared to the horizontal plane (19 presentations of each direction).

The stimulus was a series of two white noise bursts (frequency range from 80 Hz to 18 kHz) with individual lengths of 150 ms including 10-ms cosine ramps, separated by 40 ms silence. The short length was chosen to avoid perceivable effects of head motion with the static synthesis, and two bursts were presented to improve the perception of temporal cues ([Blauert, 1997](#)). The level was 60 dB SPL ± 2 dB random variation referenced to the free field.

E. Procedure

Each subject participated in three experimental sessions. First, they underwent a training session with ten runs, five runs for each the median and horizontal localization task. In each run, every incidence direction was presented in random order 3 and 2 times for the median and horizontal plane, respectively, to get a similar number of trials. The first two runs in each plane task were free-field presentations. Subsequently, three runs of virtual presentations were performed where the HRTF at the ear canal entrance (diffuse-field equalized, see [Sec. IID](#)) was used, which is the reference condition in virtual presentation. The horizontal and median plane localization runs were performed in subsequent blocks, with the order of these blocks randomized.

The two other sessions included the main experiments for horizontal and median plane localization separately, in randomized session order. Each of these sessions started with one run of free-field presentation, followed by one training run of virtual presentation with the reference condition. Then followed the main experiment, where all test conditions (see [Sec. IID](#)) were interleaved and presented in randomized order. After each 80 stimuli, the subjects had the opportunity to take a break, and the experiment was continued upon their notification. Only the data from the main experiment is evaluated in the following. Feedback about the response, i.e., showing the correct incidence direction by button markup, was provided in the training runs but not in the main experiment. The individual sessions lasted between 60 and 90 min, depending on the subject.

TABLE I. Conditions presented in the experiment, marked by “M” if included in the median plane, and “H” if included in the horizontal plane localization experiment (see Sec. II E). Every incidence direction was presented once to each subject, except in the ECEbl-DFeq (reference) condition, where each direction was repeated three times.

		Microphone Location					
		ECEbl	InsertHP	ITEind Entr	ITEind Concha	ITEgen	BTE
Processing Scheme		Ear canal entrance	Insert earphone	Individual in-the-ear device	Individual in-the-ear device	Generic in-the-ear device	Behind-the-ear device
		DFeq diffuse-field equalized	H M (3x)	H M	H M	H M	H M
	FFeq free-field equalized			H M			H M
	DFeq-LP low-pass	M	M	M	M	M	M
	HA1 Processing w. delay and comb-filter reduction	H M		H M			H M
	HA2 Processing w. delay	H M		H M			H M
	DFeq-KEMAR	H M		H M			H M
	DFeq-LP-KEMAR	M		M			M

F. Data analysis and error metrics

For the evaluation, the interaural polar coordinate system was used. It is composed of the lateral angle $\alpha \in [-90^\circ, 90^\circ]$, which denotes the lateral displacement from the median plane (negative values indicating the left-hand hemisphere). The polar angle $\beta \in [-90^\circ, 270^\circ[$ describes the position inside a sagittal plane—for the median plane, 0° denotes frontal, 90° above, and 180° rear incidence.

Two different error metrics were used for the horizontal and median plane experiments independently. Generally, two different metrics were employed to separate small localization errors from gross errors, such as front-back confusions (Carlile *et al.*, 1997). For all metrics, the result for each subject was calculated for each condition independently, i.e., a combination of microphone location and processing scheme. Lateral sound localization was assessed using the lateral error in the horizontal plane experiment. It is defined as the root-mean-square error between presentation and response lateral angles, with possible front/back errors disregarded. Vertical sound localization was assessed using the rate of front-back confusions from the horizontal plane experiment, as well as the local polar error and the quadrant errors based on the median plane experiment. The local polar error is defined as the root-mean-square error angular difference between presentation and response polar angle; where responses with an absolute error $\geq 90^\circ$ were excluded. Contrarily, the quadrant error is defined as the percentage of responses where the deviation to the presented incidence was $\geq 90^\circ$ (Middlebrooks, 1999). Whereas the local polar error measures the performance for fine localization, the quadrant error indicates the ability to perform coarse localization, similar to front-back confusions in the horizontal plane.

The data from subjects were excluded from further analysis if their localization performance with the reference condition in the main experiment was very poor, which would indicate either poor concentration or general spatial hearing

deficits. The exclusion boundaries were defined based on the present free-field localization performance as: Lateral error $>15^\circ$, front-back confusions $>25\%$, local polar error $>50^\circ$, and quadrant errors $>8\%$. Local and quadrant polar errors are codependent, therefore data from subjects who exceeded the exclusion boundary in either metric were excluded from both metrics. Contrarily, for lateral errors and front-back confusions the exclusion was made independently.

III. RESULTS & ANALYSIS

A. HRTFs and interaural cues

Sample HRTFs of one subject are depicted in Fig. 3 for three incidence directions in the median plane. In all panels, the top curve (ECEbl, DFEq) is the reference HRTF. Up to

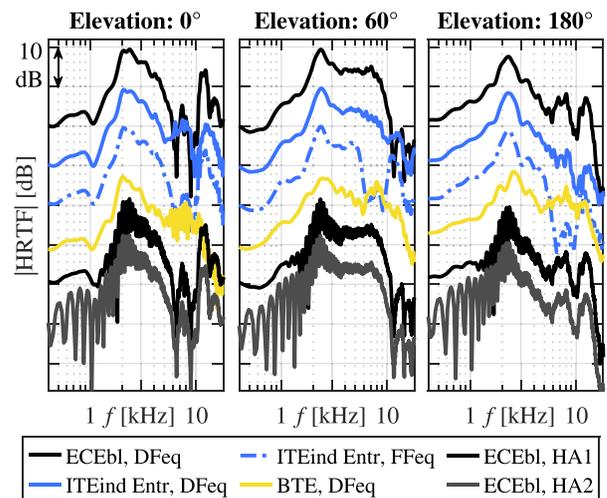


FIG. 3. (Color online) Sample HRTFs, left ear of VP_E1 (22 Hz resolution). Three incidence directions from the median plane are shown in the individual panels, colors indicate different combinations of microphone location and processing. Individual curves were shifted by 10 dB for better display. See Table I for an explanation of the conditions.

about 4 kHz, all HRTFs capture the coarse features of the reference well. Distinct differences are evident for the equalized HRTFs obtained at the ITEind_Entr and BTE microphone locations. The effect of free-field versus diffuse-field equalization is shown for the ITEind_Entr location. As compared to diffuse-field equalization, free-field equalization results in a smaller difference to the ECEbl-HRTF for frontal incidence, but a larger deviation at other incidence directions. Generally, the direction-dependent deviation to the reference HRTF is larger for the BTE than for the ITEind_Entr (Denk *et al.*, 2018b).

The effect of hearing device delay is shown for the ECEbl microphone location in the two curves at the bottom (HA1 versus HA2). While both curves match the reference HRTF in the coarse shape, the delay leads to comb filtering effects visible here as spectral ripple. Above 2.5 kHz, the ripple declines for both conditions as a result of the attenuation of the leakage component. The filter design used in HA1 additionally results in a reduction of the spectral ripple in the low frequencies compared to HA2 (Denk *et al.*, 2018d).

Figure 4 shows the interaural cues (ILD and ITD) for four sample conditions in subject VP_E1. The spectral power and unwrapped phase of the resulting HRTFs were smoothed independently to auditory resolution of one ERB (Breebart and Kohlrausch, 2001) prior to calculating the interaural transfer function, out of which ILD and ITD were calculated for the indicated frequencies (Blauert, 1997; Katz and Noisternig, 2014). The broadband ILD was calculated by taking the broadband energy ratio between the HRTFs at both ears.

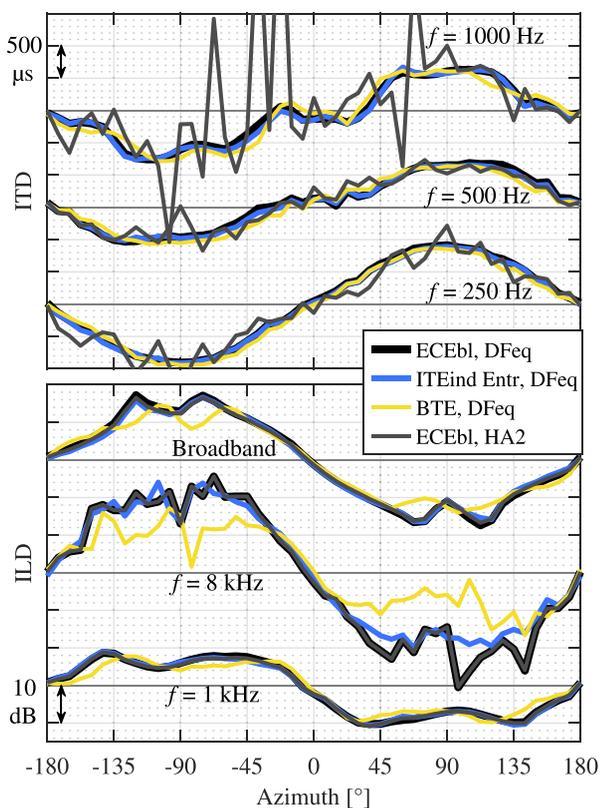


FIG. 4. (Color online) ITD (upper panel) and ILD (lower panel) in the horizontal plane for four sample conditions as indicated by the line color, data from subject VP_E1. See Table I for an explanation of the conditions.

For the diffuse-field equalized ITEind_Entr HRTF, no considerable differences to the reference HRTF (ECEbl) are observed at the assessed frequencies in ITD. For the ILD, small differences are seen for the 8 kHz curve, but not at 1 kHz or in the broadband ILD. At the BTE microphone location with the same processing, differences become apparent in all curves, but more pronounced for the ILD. The differences are larger at high frequencies or in the broadband case and at incidence angles around $\pm 90^\circ$.

With the hearing device processing (here HA2), no ILD distortions are apparent. However, large ITD distortions up to several milliseconds appear, most distinct for 1 kHz but also visible at the other frequencies. This corresponds well to the frequency range where the leakage component and the device output have similar amplitudes (cf., Figs. 2 and 3). It should be noted that the oscillating shape of the curves is not an artefact of a wrapping problem, since the increments are not multiples of the appropriate period length. The behaviour probably originates from a variation of the superposition of the two delayed sound sources (leakage vs hearing device output) across incidence directions that differs between the sides.

B. Localization accuracy with virtual stimuli

Most subjects were able to localize the virtual stimuli in the reference condition with comparable accuracy as the free-field stimuli in the training sessions. They also reported a good externalization of sounds in all experimental sessions, which together indicates a satisfactory quality of the binaural reproduction system and the validity of the reference condition.

The exclusion criteria led to discarding the data of two subjects for the vertical localization metrics, as well as two from the front-back confusions (in both cases VP_E9 and VP_E13). In consequence, all further evaluation includes data from 11 subjects for the lateral error and 9 subjects for the other metrics.

C. Lateral localization

Figure 5 shows the lateral errors (see Sec. II F) in the horizontal plane experiment. Within each processing scheme, the best performance is observed with the reference condition (ECEbl-DFeq). An influence of the microphone location is evident, independent of the processing scheme. For each processing scheme, the lateral error generally increases with the pre-sorting according to the distance of the microphone location from the eardrum (left to right).

The variance between subjects in the reference condition is usually smaller as compared to all other conditions (also in the other error metrics; see Figs. 6 and 7). This is mostly an artefact of a varying number of samples in the different conditions: Each incidence direction was presented three times in the reference condition but only once in the other conditions, while the error scores for one subject were calculated over all presentations in each condition. We verified that if each set of all possible incidence directions was evaluated independently in the reference condition, the variance between subjects would increase to a similar value as in the other conditions.

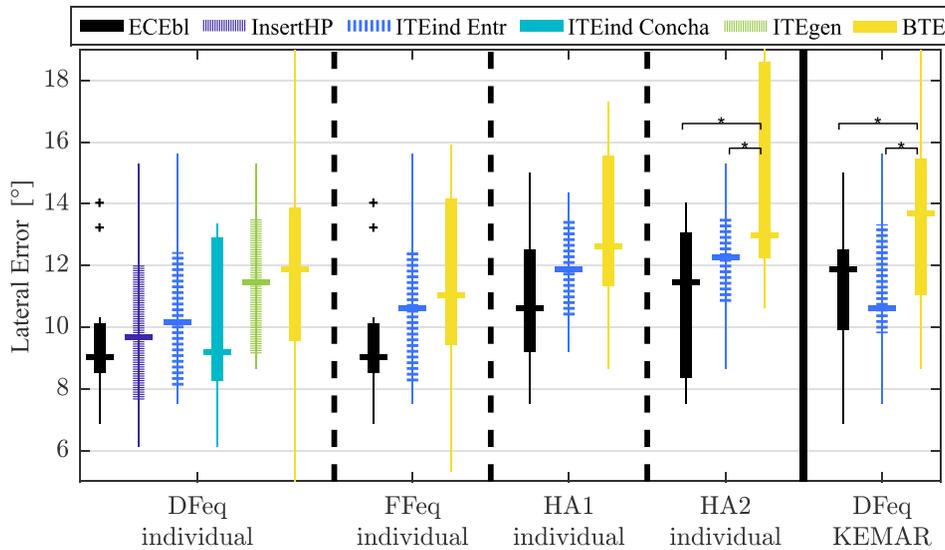


FIG. 5. (Color online) Lateral errors from the horizontal plane localization experiment. Boxes indicate the distribution of results across all subjects, the horizontal bar denotes the median, thick vertical lines the 25%–75% quantiles, thin lines the whole data range excluding outliers, which are denoted by crosses. The color indicates the microphone location, whereas the position on the x axes indicates the processing scheme. See Table I for an explanation of the conditions. Stars above horizontal brackets indicate significant *post hoc* differences between the connected conditions, *: $p < 0.05$; **: $p < 0.01$, ***: $p < 0.001$. *Post hoc* significances are only shown for effects between microphone locations, see text for further details.

A one-way repeated measures analysis of variance (rmANOVA) for the six microphone locations within DFeq revealed a statistically significant main effect [$F(1,5) = 2.93$, $p = 0.021$], but no significant *post hoc* effects between microphone locations (assessed by multiple pair-wise t -tests with Bonferroni correction). Nevertheless, a clear trend was observed with the medians differing up to 3.5° (or 40% with respect to the reference condition) between microphone conditions. The lateral error with the individual HRTF observed at the BTE and ITEgen locations is in the range of the lateral error observed with the HRTF of the KEMAR at the ECEbl location.

Furthermore, a two-way rmANOVA was performed with the factors processing scheme and microphone location (only considering ECEbl, ITEind_Entr and BTE, assessed in all processing schemes). Again, there was a significant effect of the location [$F(2,2) = 12.27$, $p = 0.0003$]. Although the processing scheme was a significant factor [$F(2,4) = 4.24$, $p = 0.0059$], the *post hoc* test revealed that significant differences only occur when comparing with the KEMAR HRTFs. Specifically, no significant difference was noted between the equalized HRTFs and the conditions including a processing

delay (HA1, HA2). However, especially for the ECEbl, there is a trend that the lateral error is increased in the HA conditions (as compared to DFeq) by about 2° or 25% with respect to the reference condition.

The results for localization using the KEMAR HRTF deviate considerably from those with individual HRTFs. The errors are generally larger, and the ranking of microphone locations changed—the lateral error is (not significantly) smaller with the ITEind_Entr location than with the ECEbl.

D. Front-back confusions in the horizontal plane

Figure 6 shows the percentage of front-back confusions (see Sec. II F) in the horizontal plane experiment. For comparison, the confusion rate for chance (i.e., random guessing) is plotted. Again, the best result is observed for the reference condition (ECEbl-DFeq); all other conditions lead to worse performance.

As for the lateral errors, an effect of the microphone location is evident independent of the processing scheme, with a ranking of microphone locations that corresponds well to the pre-sorting with increasing distance from the

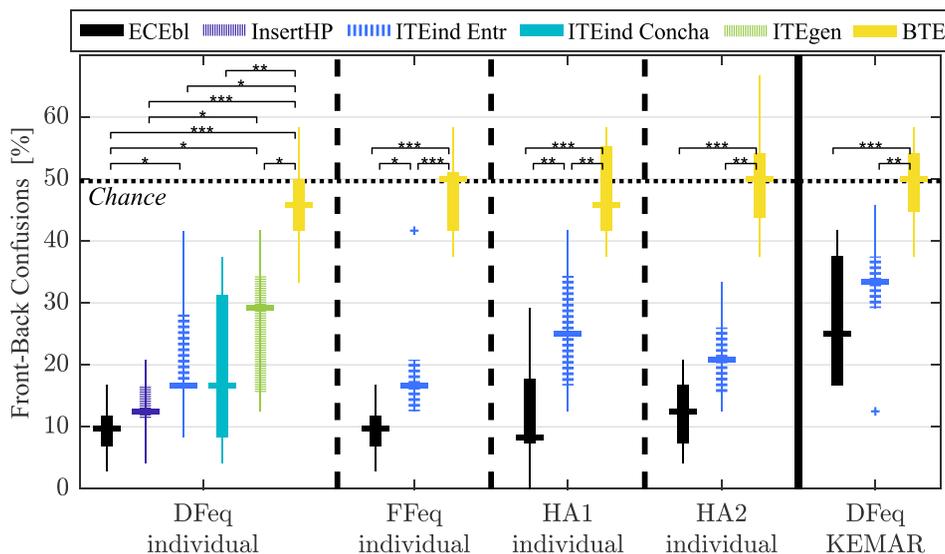


FIG. 6. (Color online) Front-back confusions from the horizontal plane localization experiment. The dotted horizontal line indicates the result for chance. All other details per Fig. 5.

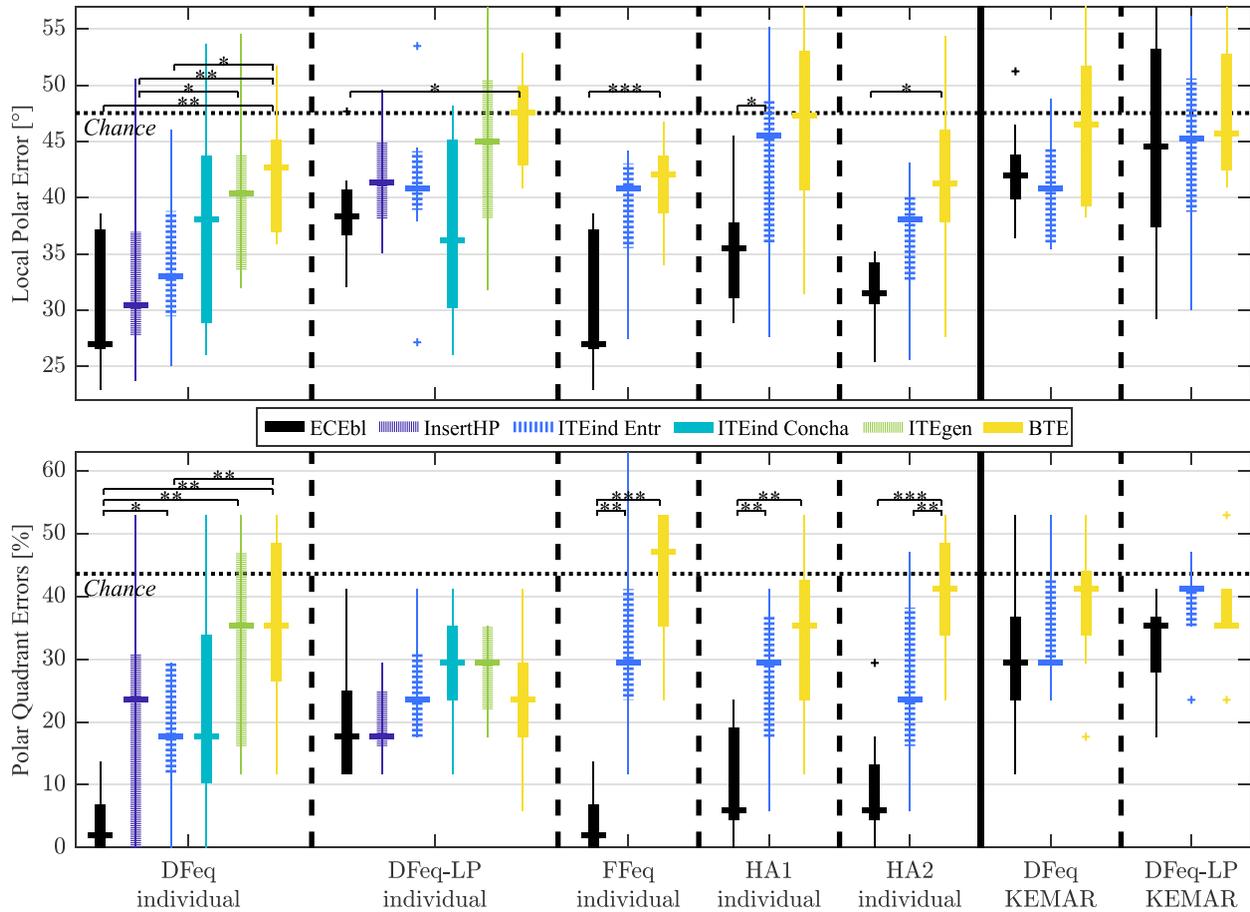


FIG. 7. (Color online) Localization errors for the median plane localization experiment: Top: Local polar error, Bottom: Polar quadrant errors. Dotted horizontal lines denote the errors for chance. All other details per Fig. 5.

eardrum (left to right). The medians of the front-back confusion rates obtained with the BTE are very close to chance. A one-way rmANOVA applied to the individual microphone locations for DFEq revealed a significant main effect [$F(1,5) = 25.96, p < 0.0001$] and significant *post hoc* differences as shown in Fig. 6. This included significant differences between the BTE and all other locations, as well as between the ECEbl and the ITEind_Entr and the ITEgen.

Again, a two-way rmANOVA was performed with the factors processing scheme and microphone location (only considering ECEbl, ITEind_Entr, and BTE). Significant main effects of processing scheme [$F(2,4) = 6.66, p = 0.0005$] and microphone location [$F(2,2) = 94.68, p < 0.0001$] as well as a significant interaction [$F(2,8) = 3.40, p = 0.0026$] were found. The *post hoc* differences between individual conditions are shown in Fig. 6, which include mostly differences between microphone locations within the individual processing schemes. Between the processing schemes, the only significant differences included comparisons with the KEMAR HRTF. This means that there was no significant difference between free- and diffuse field equalization and the HA conditions, nor a considerable trend. For the ITE_Entr and BTE locations, free-field equalization led to less front-to-back and more back-to-front confusions as compared to diffuse-field equalization.¹ However, the absolute rate of confusions was not affected.

For localization using the HRTFs obtained in the KEMAR, the ranking of microphone locations is consistent with the results of individual HRTFs. However, the differences between microphone locations are much smaller than with the individual HRTFs due to an increase of front-back confusions for the ECEbl and ITEind_Entr while the rate stays constant at chance for the BTE.

E. Localization in the median plane

Both error metrics summarizing the results from the median plane experiment are shown in Fig. 7. For comparison, the appropriate errors for chance (random guessing) are shown. As in the horizontal plane experiment, the lowest localization error is observed with the reference HRTF (ECEbl-DFEq), all other conditions lead to increased errors.

For the local polar error, the microphone location is again the governing factor for most processing schemes, and the pre-sorting with increasing distance from the eardrum (left to right) reflects well the localization results. Within the diffuse-field equalized (DFEq) microphone locations, a one-way rmANOVA revealed a significant effect of the microphone location [$F(1,5) = 6.83, p = 0.0001$]. *Post hoc* analysis showed that the local polar error in the BTE is significantly different to the ECEbl, InsertHP, and ITEind. Also, significant differences are observed between the InsertHP and the ITEgen location (see also Fig. 7). The median result with

the InsertHP is very close to the ECEbl; however, at this microphone location a large variance between subjects is observed, with an error corresponding to chance for some subjects. The differences between microphone locations are lower in the low-pass condition (DFeq-LP), with but increased errors in all locations but ITEind Concha.

A two-way rmANOVA with the factors microphone location (only ECEbl, ITEind_Entr, and BTE) and processing scheme showed a significant main effect of both factors [location: $F(2,2) = 28.51$, $p < 0.0001$, processing scheme: $F(2,6) = 7.72$, $p < 0.0001$], but no significant interaction [$F(2,12) = 1.12$, $p = 0.35$]. The *post hoc*-test showed that significant differences between processing schemes are only observed in comparisons involving KEMAR conditions, except for a significant difference between DFeq and DFeq-LP for the ECEbl microphone location. No significant difference between the equalized HRTFs and the HA conditions, nor between the HA conditions, was observed. Within the ECEbl location, the polar error is slightly increased in the HA conditions, more pronounced in HA1. Within some processing schemes, significant differences between microphone locations were noted (as plotted in Fig. 7).

For the polar quadrant errors, similar trends can be observed. Comparing the diffuse-field equalized (DFeq) HRTFs, the ECEbl has the smallest error, while at all other locations the errors are comparable in size. There, a one-way rmANOVA revealed a significant main effect [$F(1,5) = 13.20$, $p < 0.0001$] and similar *post hoc* differences as for the local polar error as shown in Fig. 7. In this error metric, smaller differences between microphone locations are observed in the low-pass condition. There, the polar quadrant error increases for the ECEbl, InsertHP, and ITEind, but decreases for the other locations. For the FFeq and HA processing schemes, the trend is similar to the DFeq: the results for the BTE microphone location is always very comparable and near chance, but differ considerably from the ECEbl. The results for ITEind_Entr are in between, with an increased error compared to ECEbl. A two-way rmANOVA and *post hoc* analysis analogous to the evaluation of local polar errors revealed significant main effects [location: $F(2,2) = 35.72$, $p < 0.0001$; processing scheme: $F(2,6) = 7.76$, $p < 0.0001$] as well as a significant interaction [$F(2,12) = 9.04$, $p < 0.0001$]. Significant *post hoc* differences were noted between the ECEbl and BTE for the FFeq and HA processing schemes, and significances between ECEbl and ITEind_Entr for most processing schemes. Between processing schemes, no significant differences were found, except when comparing to KEMAR conditions. Although there is a trend that the quadrant errors with the HA conditions were increased as compared to the equalized HRTFs, this effect did not reach significance.

For localization with the KEMAR HRTFs, the microphone location is irrelevant and both error metrics are at or near chance. This observation does not change in the low-pass condition.

Figure 8 shows the confusion matrices (i.e., angle-resolved scatter plot for responses over presentations) for all subjects and a subset of conditions. The error metrics from Fig. 7 are not sufficient to fully describe the localization disruptions. For instance, in the low-pass condition, the

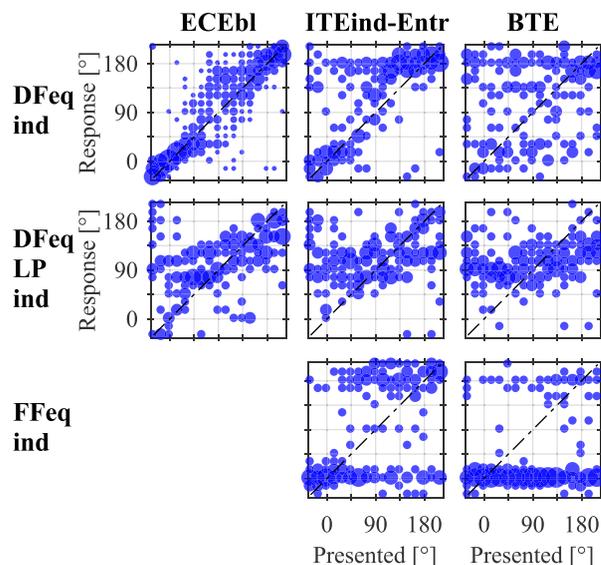


FIG. 8. (Color online) Confusion matrices in the median plane experiment, for three microphone conditions (columns) and three processing schemes (rows). The size of the dots is proportional to the numbers of responses. 0° indicates frontal, 90° above, and 180° rear sound incidence.

localization errors were smaller at the ITEind_Entr and BTE locations as compared to the full bandwidth. As demonstrated by the confusion matrices (second row compared to first row), this does not originate from better localization abilities with the restricted bandwidth. With the low-pass stimuli, subjects localized most stimuli above the head, with only little dependence on the microphone location. Only because the presented directions did not cover the whole circle and were biased to incidence from above, the resulting polar quadrant errors were smaller. Figure 8 also reveals that the increase of errors with free-field equalized as compared to diffuse-field equalized HRTFs results from systematically different localization patterns. For the FFeq processing, the majority of stimuli was localized at the frontal direction or at the rear direction near the horizontal plane. For the ITEind_Entr location, this means that the ability to perceive a coarsely correct elevation was not observed in about half of the subjects' responses with free-field equalization. For the BTE microphone, free-field equalization of the HRTF resulted in perceiving almost all median plane stimuli in the front.

For the HA1 and HA2 processing schemes, the confusion matrices are very comparable to the DFeq results (1st row) in the appropriate microphone locations. Localization with the KEMAR HRTFs led to an almost uniform distribution of responses, similar to the BTE-DFeq condition.

IV. DISCUSSION

A. Influence of the microphone location and bandwidth: Vertical localization

The location of the microphone alone produced a large disruption of vertical sound localization. The differences between locations were not substantially different when a hearing device delay was present, or when a free-field equalization was applied instead of a diffuse-field equalization. We conclude that the microphone location is the governing

factor for vertical localization with linear hearing devices in normal hearing listeners.

Vertical localization depends on spectral directional cues (Blauert, 1997). The present psychophysical results are thus well in line with the variation between HRTFs shown in Fig. 3, and model evaluations in previous studies (Denk *et al.*, 2018b; Durin *et al.*, 2014). This correspondence confirms that computational models are well suited to evaluate the effect of the microphone location on vertical localization (Baumgartner *et al.*, 2013). The present data also revealed much larger differences between microphone locations that are non-optimal, i.e., between ITE and BTE locations, than previous studies (Best *et al.*, 2010; Van den Bogaert *et al.*, 2011). Using the information from a single BTE microphone, virtually all localization metrics were at or near chance. In other words, almost no vertical sound localization seems possible based on one BTE microphone. This is well in line with results from (Best *et al.*, 2010). Contrarily, the information from an ITE microphone appears to be sufficient for a reasonable distinction between front and back, and a coarse judgement of elevation. However, the performance with ITE microphone locations was subject to large variations between listeners. The present data also provides evidence that the exact positioning in the ear and the size of the device can directly impact the vertical localization performance, most pronounced for the local polar error, but also seen for front-back confusions in the differences between the InsertHP, ITEind, and ITEgen locations. This explanation fits well with the very large between-subject variance observed in all locations but the reference location, since the exact fit of these device styles is dependent on the individual ear. The present data also shows that there is no relevant difference between two microphones included in the same ITE device with respect to sound localization, which is in line with a previous model evaluation utilizing the same data (Denk *et al.*, 2018b).

When the bandwidth was restricted to 8 kHz, the differences between microphone locations declined, but the trends mostly persisted. Moreover, the confusion matrices also showed that reduced polar quadrant errors for the low-pass condition (e.g., BTE) did not actually result from improved localization abilities, but are an artefact of the evaluation. Generally, the present results show that a restricted bandwidth is detrimental especially for good microphone locations and has no positive impact for others.

B. Influence of the microphone location: Lateral localization

The microphone location alone also had an impact on lateral localization. This aspect of localization is thought to be governed by interaural rather than monaural spectral cues. The impact of the microphone location on the ITD (shown in Fig. 4 for ITEind_Entr and BTE) was rather small at all assessed frequencies. The impact on the ILD was larger both in single auditory frequency bands as well for the whole audio bandwidth. Roughly, it can be stated that normal ITDs but distorted ILDs were available to the listeners in the DFeq conditions. Since ITD cues are thought to override

conflicting ILD (Macpherson and Middlebrooks, 2002; Wightman and Kistler, 1992), we had expected no influence of the microphone location on the lateral error.

However, the results show that a non-optimal microphone location alone impairs lateral sound localization. While the differences did not reach significance in the present evaluation, clear trends were noted. Specifically, with the BTE and ITEgen microphone locations, the performance in lateral localization was as poor as when listening through a KEMAR. This impairment due to the microphone location results from biased spectral directional cues only and thus probably reflects a reduced spatial fidelity and increased localization blur. Previous studies using hearing-impaired listeners wearing hearing aids (Best *et al.*, 2010; Van den Bogaert *et al.*, 2011) or normal-hearing listeners wearing electronic hearing protectors (Brungart *et al.*, 2003, 2007) found no or a minor influence of the microphone location on lateral localization. In those studies, these rather subtle errors were probably overwhelmed by more prominent errors related to the devices like bandwidth limitations or nonlinearities, or effects of hearing impairment (Byrne and Noble, 1998).

As for vertical localization, microphone positioning in the ear leads to poorer performance than with an optimal location, but to better performance than with a BTE microphone. Small differences are again apparent between the individual ITE microphone locations; mostly showing that the localization errors increase when the microphone sticks out of the ear (as in the ITEgen).

We want to note again that this condition includes no vent, i.e., no acoustic leakage component that might contain unbiased directional information is present. The influence of a vent is discussed in Sec. IV D.

C. Free- versus diffuse-field equalization and implications for directional microphones

Diffuse- and free-field equalization produced no considerably different results for lateral localization, but large differences for vertical localization. The application of free-field equalization (for the ITEind and BTE microphone location) made it almost impossible for the subjects to perceive sounds to be displaced from the horizontal plane (Fig. 8). While for the ITEind_Entr location, this resulted in an impairment of elevation judgements as compared to diffuse-field equalization, for the BTE it resulted in a perception of most stimuli from the front, rather than a very random localization pattern as observed with diffuse-field equalization. The large impact is rather surprising, given that the only difference between the conditions is a constant spectral offset, namely, a notch between 4 and 10 kHz that is typical for frontal incidence (cf., Denk *et al.*, 2018a).

The results show that the overall frequency response characteristics of a hearing device have an influence sound localization. Diffuse-field equalization of the hearing device microphone leads to better localization performance than free-field equalization. Whereas diffuse-field equalization seems to better allow utilizing the residual spectral directional cues captured by the device microphone, free-field

very effectively “drags” the apparent location of a source towards the front and, more importantly, towards the horizontal plane in general.

If more than one microphone is available, many hearing devices include directional microphones for noise reduction purposes (Doclo *et al.*, 2015). Generally, directional microphones can provide a benefit for localization, mostly front-to-back confusions (Van den Bogaert *et al.*, 2011), even if the generated cues are not necessarily consistent with natural spectral cues. The results for the effect of the microphone location demonstrate that directional microphones should be designed to not additionally disrupt spectral directional cues. Directional microphones could also be designed to restore parts of the pinna cues that are not captured by the device microphones (Schinkel-Bielefeld *et al.*, 2018), which is equivalent to a direction-dependent free-field equalization. The present results demonstrate the potential positive impact of such approaches on sound localization and provide starting points for further refinements.

D. Influence of a vent and delayed hearing device output

The influence of a vent and processing delays generally showed no large effect on the vertical plane localization performance. Apparently, the spectral ripple created by the delay did not significantly bias the relevant spectral directional cues. In particular, the greatest importance of these cues is above 4 kHz (King and Oldfield, 1997), where the ripple declined in the present data. Also, the lower spectral resolution of the auditory system with increasing frequency reduces the perceived spectral distortions. Nevertheless, small increments in vertical localization errors were noted between the equalized hearing device HRTF and the delay condition. Given that this increment was smaller for front-back confusions and polar quadrant errors than for local polar errors, an increased apparent source width would be a suitable model to explain the impact of the hearing device delay on vertical sound localization.

For lateral localization, the impact of the vent and hearing device delay was larger. That is, the lateral error increased in HA conditions as compared to the DFeq condition, for each microphone location. This indicates that the disturbing effect of a delay is approximately additive to the effect of the microphone location. Also, there is a trend that the lateral errors were larger when using the filter design from HA2, i.e., producing a larger frequency region where leakage and hearing device output overlap. In the present results, the leakage component that directly enters the ear canal and carries unbiased directional cues in the low-frequency regime did not improve lateral sound localization, although improving sound localization is one of the many motivations behind using a vent or even open-fit devices (Akeroyd and Whitmer, 2016; Noble *et al.*, 1998). The detrimental influence of a vent in the current data can probably be explained by the disturbing effect of the superposition with the delayed hearing device output. The potentially beneficial effects of a vent might better come into effect when spectral overlap between the leakage and the

hearing device output is avoided, or the cut-off frequency of the leakage component is increased.

Considering these results and also the evaluation of interaural cues from Fig. 4 (processing contains delays included in ECEbl-HA2), we assume that the impairment of lateral sound localization due to the delayed hearing device output originates from fluctuations of the ITD. Such uncertainties have been identified as a contributor to increased source widths (Käsbach *et al.*, 2014), and increased source widths have been observed when listening through hearing devices (Cubick *et al.*, 2018). The effects on lateral localization were slightly reduced by minimizing the comb-filtering effects using a suitable output filter design (Denk *et al.*, 2018d), which largely eliminated the low-frequency output of the device in the frequency region of overlap with the direct sound component and thus reduced ITD distortions (see Fig. 3, bottommost curves). It is hard to assess to what extent the precedence effect plays a role in suppressing the perceptual effects of the delayed hearing device output, given that the spatial location of both signal components is equal, unlike in most studies on the effect of an echo (Brown *et al.*, 2015).

E. Evaluation using dummy head HRTFs

When stimuli based on measurements on a KEMAR were utilized, the obtained localization results changed. More importantly, the variation was different between microphone locations, and also between error metrics. In all cases, the differences between the microphone locations were smaller with the KEMAR data than in the individual evaluation. Also, the performance for each microphone location was worse with the KEMAR, except when it was already at chance with the individual HRTFs (e.g., front-back confusions with the BTE). For the lateral error, the ordering of microphone locations was changed between the individual and KEMAR data. In summary, the data show that a mannequin generally is not suitable as a basis for a psychophysical assessment of localization performance with hearing devices.

Utilizing a different dummy head than the KEMAR is not expected to change or even improve this result. Among commercially available dummy heads, the KEMAR HRTFs produced model localization predictions that were most consistent with individual HRTFs (Denk *et al.*, 2018b). The inconsistency between the present results with dummy head and individual HRTFs is probably caused by a different bias originating from the non-optimal microphone location in different ears, and a superposition with the localization deficits when listening through a non-familiar HRTF.

V. CONCLUSIONS

For normal hearing subjects listening through linear hearing devices without directional microphones, and when no dynamic binaural cues are available, the following conclusions are drawn:

- (i) The microphone location is the governing factor for sound localization abilities. A non-optimum microphone location disrupts sound localization in the

vertical domain, and reduces the accuracy in lateral localization. Microphones located inside the cavum conchae generally lead to better localization results than BTE microphones or microphones of ITE devices that stick out of the pinna. However, localization performance is decreased as compared to microphones located in the ear canal.

- (ii) A bandwidth beyond 8 kHz is a key factor to full localization fidelity, independent of the microphone location.
- (iii) A processing delay of 6 ms that is synchronous between the ears, together with a vent that allows low-frequency sound to directly leak into the ear canal, has little to no influence on sound localization in the vertical domain. Such delay artefacts led to a trend towards a negative effect on lateral localization; however, it did not reach significance in the present experiment. Reducing the delay artefacts by appropriate filtering of the hearing device output did not affect localization performance as compared to the baseline processing.
- (iv) Sound localization is not independent of the frequency response characteristics of the hearing device. To optimally exploit spectral cues captured by the microphone and improve localization performance, the frequency response of hearing devices should be equalized to the diffuse rather than to the free-field response of the open ear.
- (v) Dummy head recordings are unsuitable for evaluating the impact of hearing devices on individual localization performance in psychophysical experiments.

ACKNOWLEDGMENT

This research was funded by the German Research Council DFG through the Collaborative Research Center SFB1330 HAPPA—Project No. 352015383 A4 and C5, as well as the by the European Regional Development Fund ERDF, Project *VIBHear*. We thank Steven van de Par for helpful discussions regarding the experimental design, Bernhard Eurich for conducting parts of the listening experiments, and our motivated subjects for participation.

¹Percentage of front-to-back reversals within all front-back confusions, mean \pm standard deviation across subjects: ITE-DFFeq $58 \pm 39\%$, ITE-FFeq $38 \pm 24\%$, BTE-DFFeq $56 \pm 19\%$, BTE-FFeq $27 \pm 10\%$. Percentage of back-to-front reversal is 100% minus given values, standard deviations are identical.

- Akeroyd, M. A., and Whitmer, W. M. (2016). "Spatial hearing and hearing aids," in *Hearing Aids*, edited by G. R. Popelka, B. C. J. Moore, R. R. Fay, and A. N. Popper (Springer International Publishing, Cham, Switzerland), pp. 181–215.
- Baumgartner, R., Majdak, P., and Laback, B. (2013). "Assessment of sagittal-plane sound localization performance in spatial-audio applications," in *The Technology of Binaural Listening, Modern Acoustics and Signal Processing*, edited by J. Blauert (Springer, Berlin-Heidelberg), pp. 93–119.
- Best, V., Kalluri, S., McLachlan, S., Valentine, S., Edwards, B., and Carlile, S. (2010). "A comparison of CIC and BTE hearing aids for three-dimensional localization of speech," *Int. J. Audiol.* **49**, 723–732.

- Blauert, J. (1997). *Spatial Hearing: The Psychophysics of Human Sound Localization* (MIT Press, Cambridge, MA), p. 510.
- Breebart, J., and Kohlrausch, A. (2001). "Perceptual (ir)relevance of HRTF magnitude and phase spectra," *Audio Eng. Soc. Conv.* **110**, 1–9.
- Brown, A. D., Stecker, G. C., and Tollin, D. J. (2015). "The precedence effect in sound localization," *J. Assoc. Res. Otolaryngol.* **16**, 1–28.
- Brungart, D. S., Hobbs, B. W., and Hamil, J. T. (2007). "A comparison of acoustic and psychoacoustic measurements of pass-through hearing protection devices," in *Proceedings of the 2007 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, October 21–24, New Paltz, New York, pp. 70–73.
- Brungart, D. S., Kordik, A. J., Eades, C. S., and Simpson, B. D. (2003). "The effect of microphone placement on localization accuracy with electronic pass-through earplugs," in *Proceedings of the 2003 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, October 21–24, New Paltz, New York, pp. 149–152.
- Byrne, D., and Noble, W. (1998). "Optimizing sound localization with hearing aids," *Trends Amplif.* **3**, 51–73.
- Carlile, S., Leong, P., and Hyams, S. (1997). "The nature and distribution of errors in sound localization by human listeners," *Hear. Res.* **114**, 179–196.
- Cubick, J., Buchholz, J. M., Best, V., Lavandier, M., and Dau, T. (2018). "Listening through hearing aids affects spatial perception and speech intelligibility in normal-hearing listeners," *J. Acoust. Soc. Am.* **144**, 2896–2905.
- D'Angelo, W. R., Bolia, R. S., Mishler, P. J., and Morris, L. J. (2001). "Effects of CIC hearing aids on auditory localization by listeners with normal hearing," *J. Speech Lang. Hear. Res.* **44**, 1209–1214.
- Denk, F., Ernst, S. M. A., Ewert, S. D., and Kollmeier, B. (2018a). "Adapting hearing devices to the individual ear acoustics: Database and target response correction functions for various device styles," *Trends Hear.* **22**, 2331216518779313.
- Denk, F., Ewert, S. D., and Kollmeier, B. (2018b). "Spectral directional cues captured by hearing device microphones in individual human ears," *J. Acoust. Soc. Am.* **144**, 2072–2087.
- Denk, F., Kollmeier, B., and Ewert, S. (2018c). "Removing reflections in semiaechoic impulse responses by frequency-dependent truncation," *J. Audio Eng. Soc.* **66**, 146–153.
- Denk, F., Schepker, H., Doclo, S., and Kollmeier, B. (2018d). "Equalization filter design for achieving acoustic transparency in a semi-open fit hearing device," in *Proceedings of 13 ITG Conference on Speech Communication*, October 10–12, Oldenburg, Germany, pp. 226–230.
- Doclo, S., Kellermann, W., Makino, S., and Nordholm, S. E. (2015). "Multichannel signal enhancement algorithms for assisted listening devices: Exploiting spatial diversity using multiple microphones," *IEEE Signal Process. Mag.* **32**, 18–30.
- Durin, V., Carlile, S., Guillon, P., Best, V., and Kalluri, S. (2014). "Acoustic analysis of the directional information captured by five different hearing aid styles," *J. Acoust. Soc. Am.* **136**, 818–828.
- Groth, J., and Søndergaard, M. B. (2004). "Disturbance caused by varying propagation delay in non-occluding hearing aid fittings," *Int. J. Audiol.* **43**, 594–599.
- Härmä, A., Jukka, J., Tikander, M., Karjalainen, M., Lokki, T., Hiipakka, J., and Lorho, G. (2004). "Augmented reality audio for mobile and wearable appliances," *J. Audio Eng. Soc.* **52**, 618–639.
- Hoffmann, P., Möller, A. K., Christensen, F., and Hammershøi, D. (2014). "Sound localization and speech identification in the frontal median plane with a hear-through headset," in *Proceedings of Forum Acusticum*, September 7–12, Krakow, Poland, pp. 1–6.
- Jensen, N. S., Neher, T., Laugesen, S., Johannesson, R. B., and Kragelund, L. (2013). "Laboratory and field study of the potential benefits of pinna cue-preserving hearing aids," *Trends Amplif.* **17**, 171–188.
- Käsbach, J., May, T., Oskarsdottir, G., Jeong, C.-H., and Chang, J. (2014). "The effect of interaural-time-difference fluctuations on apparent source width," in *Proceedings of Forum Acusticum*, September 7–12, Krakow, Poland, pp. 1–5.
- Katz, B. F. G., and Noisternig, M. (2014). "A comparative study of interaural time delay estimation methods," *J. Acoust. Soc. Am.* **135**, 3530–3540.
- Killion, M. C., Monroe, T., and Drambarean, V. (2011). "Better protection from blasts without sacrificing situational awareness," *Int. J. Audiol.* **50**, S38–S45.
- King, R. B., and Oldfield, S. R. (1997). "The impact of signal bandwidth on auditory localization: Implications for the design of three-dimensional audio displays," *Human Factors* **39**, 287–295.

- Kollmeier, B., and Kiessling, J. (2018). "Functionality of hearing aids: State-of-the-art and future model-based solutions," *Int. J. Audiol.* **57**, S3–S28.
- Macpherson, E. A., and Middlebrooks, J. C. (2002). "Listener weighting of cues for lateral angle: The duplex theory of sound localization revisited," *J. Acoust. Soc. Am.* **111**, 2219–2236.
- Marentakis, G., and Liepins, R. (2014). "Evaluation of hear-through sound localization," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems ACM*, April 26–May 1, Toronto, Canada, pp. 267–270.
- Middlebrooks, J. C. (1999). "Virtual localization improved by scaling non-individualized external-ear transfer functions in frequency," *J. Acoust. Soc. Am.* **106**, 1493–1510.
- Møller, H. (1992). "Fundamentals of binaural technology," *Appl. Acoust.* **36**, 171–218.
- Møller, H., Hammershøi, D., Jensen, C. B., and Sørensen, M. F. (1995). "Transfer characteristics of headphones measured on human ears," *J. Audio Eng. Soc.* **43**, 203–217.
- Nishino, T., Kajita, S., Takeda, K., and Itakura, F. (1999). "Interpolating head related transfer functions in the median plane," in *Proceedings of the 1999 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, October 20, New Paltz, New York, pp. 167–170.
- Noble, W., Byrne, D., and Ter-Horst, K. (1997). "Auditory localization, detection of spatial separateness, and speech hearing in noise by hearing impaired listeners," *J. Acoust. Soc. Am.* **102**, 2343–2352.
- Noble, W., Sinclair, S., and Byrne, D. (1998). "Improvement in aided sound localization with open earmolds: Observations in people with high-frequency hearing loss," *J. Am. Acad. Audiol.* **9**, 25–34.
- Schinkel-Bielefeld, N., Oreinos, C., and Kamkar, H. P. (2018). "Improving localization in binaural beamforming for hearing aid wearers," in *Proceedings of the Speech in Noise Workshop 2018*, January 11–12, Glasgow, UK.
- Stone, M. A., Moore, B. C. J., Meisenbacher, K., and Derleth, R. P. (2008). "Tolerable hearing aid delays v estimation of limits for open canal fittings," *Ear Hear.* **29**, 601–617.
- Tikander, M. (2009). "Usability issues in listening to natural sounds with an augmented reality audio headset," *J. Audio Eng. Soc.* **57**, 430–441.
- Van den Bogaert, T., Carette, E., and Wouters, J. (2011). "Sound source localization using hearing aids with microphones placed behind-the-ear, in-the-canal, and in-the-pinna," *Int. J. Audiol.* **50**, 164–176.
- Van den Bogaert, T., Klasen, T. J., Moonen, M., Van Deun, L., and Wouters, J. (2006). "Horizontal localization with bilateral hearing aids: Without is better than with," *J. Acoust. Soc. Am.* **119**, 515–526.
- Wightman, F. L., and Kistler, D. J. (1992). "The dominant role of low-frequency interaural time differences in sound localization," *J. Acoust. Soc. Am.* **91**, 1648–1661.