Horizontal localization with bilateral hearing aids: Without is better than with

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This paper studies the effect of bilateral hearing aids on directional hearing in the frontal horizontal plane. Localization tests evaluated bilateral hearing aid users using different stimuli and different noise scenarios. Normal hearing subjects were used as a reference. The main research questions raised in this paper are: (i) How do bilateral hearing aid users perform on a localization task, relative to normal hearing subjects? (ii) Do bilateral hearing aids preserve localization cues, and (iii) Is there an influence of state of the art noise reduction algorithms, more in particular an adaptive directional microphone configuration, on localization performance? The hearing aid users were tested without and with their hearing aids, using both a standard omnidirectional microphone configuration and an adaptive directional microphone configuration. The following main conclusions are drawn. (i) Bilateral hearing aid users perform worse than normal hearing subjects in a localization task, although more than one-half of the subjects reach normal hearing performance when tested unaided. For both groups, localization performance drops significantly when acoustical scenarios become more complex. (ii) Bilateral, i.e., independently operating hearing aids do not preserve localization cues. (iii) Overall, adaptive directional noise reduction can have an additional and significant negative impact on localization performance. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2139653]

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I. INTRODUCTION

Selective hearing is a useful mechanism for extracting desired signals in complex acoustic environments, such as a cocktail party. The ability to understand speech in these complex scenarios has been largely attributed to the binaural processing strategy used in the auditory system (Bronkhorst and Plomp, 1988, 1989). Information from both ears interacts at various subcortical structures thereby providing the listener with the information needed to reconstruct the auditory scene. This helps the listener to stay focussed on one sound source and to cancel out unwanted sound sources. This paper studies one of the binaural processes, namely sound localization. The main mechanisms used for sound localization are fairly well known. Localization involves binaural processing of very small differences in time (10–700 μs), intensity (0–20 dB), and spectrum between the two ears (Stevens and Newman, 1936; Blauert, 1997; Gilkey and Anderson, 1997; Hartmann, 1999; Langendijk and Bronkhorst, 2002). Extensive psychoacoustical research has been done on localization: Experiments to measure localization performance of normal hearing (Makous and Middlebrooks, 1990; Hofman and Van Opstal, 1998; Lorenzi *et al.*, 1999b) and hearing impaired subjects (Hausler *et al.*, 1983; Noble *et al.*, 1994; Lorenzi *et al.*, 1999a) with different stimuli and in different test conditions, experiments under headphones with isolated or conflicting cues (Wightman and Kistler, 1992; Lorenzi *et al.*, 1999b), comparing performance of a monaural hearing aid or cochlear implant configuration with a bilateral hearing aid or cochlear implant configuration (Dillon, 2001; Van Hoesel and Tyler, 2003), and many others. Although a lot of work has been done on localization with normal hearing and hearing impaired subjects, little work has questioned the effect of a bilateral hearing aid system on the binaural potential of the hearing aid user. In the human auditory system, the acoustical input signals of both ears are linked to the binaural centers where the binaural cues are interpreted and processed. Adding independently working hearing aids, each using its own compression scheme, introducing its own time delay (in the order of 5 to 10 ms) (Dillon *et al.*, 2003) and

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having independent noise reduction schemes, could have a destructive effect on the binaural cues. Correspondingly, the hearing aid user's localization performance and speech perception in a complex environment could also be degraded.

In the work of Hausler *et al.* (1983), the question was raised as to whether hearing aids could have an impact on sound localization performance. Noble and Byrne (1990) tested localization performance in the frontal horizontal and vertical planes with bilateral behind the ear (BTE), in the ear (ITE), and in the canal (ITC) hearing aids with omnidirectional microphone configurations. A normal hearing group was used as a reference. Intrasubject analysis did not show significant differences between unaided and aided performance for all three groups. These analyses were done on an error measure in which both vertical and horizontal errors were included. No statistical analysis on only horizontal or on only vertical localization errors was presented in the study. However, Noble and Byrne stated that for the control group, i.e. a group of six normal hearing subjects, horizontal localization performance dropped from nearly 100% correct unaided to 73% correct wearing BTE hearing aids. In the same study, it is mentioned that the hearing aid users tended to show poorer aided than unaided localization performance in the frontal horizontal plane, except for the ITE hearing aid users, when wearing their own hearing aids. The difference in horizontal localization performance was not quantified in the study.

Later, Noble *et al.* (1998) and Byrne *et al.* (1998) showed that better performance could be obtained by using open earmolds instead of closed earmolds for subjects with a moderate high-frequency (and a severe low-frequency loss) or a moderate low-frequency (and a severe high-frequency) hearing loss. By using open earmolds, the subject can use the direct soundfield in the region of the moderate hearing loss for localization. For subjects with a moderate high-frequency loss, improvement in the vertical plane was found. For subjects with a moderate low to midfrequency hearing loss, improvement in the horizontal plane was found and performance was restored to unaided performance. These studies suggest that bilateral BTE hearing aids do not preserve localization cues. In all three studies, a broadband pink noise target stimulus was used and no jammer sources were present.

The available processing power in hearing aids increases as technology evolves. One of the main benefits is that more complex noise reduction algorithms can be implemented, improving speech understanding performance in acoustically challenging scenarios. In recent years, good results have been obtained using adaptive filtering techniques. These techniques adapt according to changes in noise scenario or acoustic condition, but are typically designed and evaluated monaurally. An important question is whether using these techniques bilaterally can have an impact on a binaural process, in particular on localization.

This paper studies localization performance of bilateral BTE hearing aid users in the frontal horizontal plane. The main cues for sound localization in these tests are interaural time differences (ITD) and interaural level differences (ILD). This study questions and quantifies the effect of current signal processing techniques on localization performance. By using low-and high-frequency stimuli, it tries to determine which cues are being affected by the different signal processing strategies. The following research questions are addressed in this paper: (i) How well do bilateral hearing aid subjects, relative to normal hearing persons, perform on a localization task using low-frequency, high-frequency and broadband signals and what is the influence of jammer sources on localization performance? (ii) Do modern digital hearing aids preserve localization cues and hence can hearing aid users use the full potential of their binaural processing capabilities? (iii) Do noise reduction systems have an influence on localization performance? The noise reduction technique tested was an adaptive directional microphone configuration, which is implemented in today's state of the art hearing aids. Data were gathered from hearing impaired subjects with and without hearing aids to test the impact of their hearing aids. A group of normal hearing subjects was used as a reference. The hearing aids were fitted with a nonadaptive omnidirectional microphone configuration and an adaptive directional microphone configuration. Low-frequency, high-frequency, and broadband signals were used to separate the effects on ITD and ILD processing. Jammer sources were added to the condition with the broadband signal to evaluate the impact of the noise reduction system.

II. METHODS

A. Subjects

Prior to the study with the hearing impaired subjects, a similar study was performed with ten normal hearing subjects between 20 and 25 years old (average age: 22 years old). Mean audiometric data of the normal hearing subjects are given in Table I. These subjects have a maximum hearing threshold of 20 dB hearing level (HL) on all octave frequencies starting from 125 Hz up to 8000 Hz. The relevant data of the normal hearing group will be described and used as a reference for the hearing impaired group.

Ten hearing impaired subjects, ranging from 44 to 79 years old, participated in this study. All of them are experienced bilateral hearing aid users. Six of them use Phonak, Switzerland, Perseo hearing aids, three use GNResound, Denmark, Canta7 hearing aids, and one of the test persons uses Widex, Denmark, Diva hearing aids. The settings of their everyday hearing aids were copied into another pair of hearing aids of the identical brand and type, and monaural spectral enhancement techniques were switched off in the Canta7 and Perseo devices. Audiometric data of the hearing impaired subjects are given in Table I. The mean absolute difference between left and right hearing loss is less than 10 dB for all subjects, except for subject ML who has a larger asymmetrical hearing loss. The subjects used their own earmolds with a venting between 1 and 3 mm, except for subject ML who used an open venting on her best ear for otological reasons. The amplification levels of all subjects did not show big asymmetrical settings (<7 dB difference between the mean left and right amplification levels at an input level of 50 dB sound pressure level (SPL) (G50) and <7 dB difference for the mean left and right amplification

TABLE I. The audiometric data (in dB HL) of the 10 hearing impaired (HI) subjects and the mean audiometric data of the 10 normal hearing (NH) subjects.

		Right ear (Hz)							Left ear (Hz)						
Subject	Hearing aid type	250	500	1 k	2 k	4 k	6 k	8 k	250	500	1 k	2 k	4 k	6 k	8 k
AP	Perseo 211	55	50	45	40	55	60		35	35	45	55	60	60	
BG	Canta 7	35	35	40	40	45	30		40	35	35	35	35	25	
BJ	Perseo 211	25	35	40	40	45	55		35	40	45	45	60	60	
CH	Perseo 111	45	35	35	50	80	100		40	30	35	70	80	105	
DH	Perseo 211	30	30	40	40	40	45		35	30	45	50	45	50	
MA	Canta 7	15	10	30	55	60	45		25	25	30	55	55	45	
ML	Diva	35	55	65	60	70	80		15	25	35	40	55	75	
SM	Canta 7	45	40	35	45	55	60		50	50	40	60	55	60	
VP	Perseo 111	25	30	35	35	50	60		20	20	30	35	45	55	
VM	Perseo 211	50	50	45	50	50	45		50	55	50	50	50	50	
Mean HI		36	37	41	46	55	58		35	35	39	50	54	59	
StDev HI		13	13	10	8	12	20		12	11	7	11	12	21	
Mean NH		−3	1	4	3	3		14	4	5	8	5	10		11
StDev NH		9	6	7	7	5		6	6	4	3	5	7		6

levels at an input level of 80 dB SPL (G80) at all frequencies), except for subject ML who had asymmetrical amplification levels to compensate for the asymmetrical hearing loss. However, this subject did not show a bias with (on average 5°) or without hearing aids (on average 2°), and showed results similar to all other subjects.

B. Setup

Tests were carried out in a reverberant room with dimensions 6 m × 3 m × 3.5 m (length × width × height) and a reverberation time, *T*60, of 0.54 s as determined for a speech weighted noise spectrum. Test persons were placed inside an array of 13 single-cone speakers with a cone diameter of 10 cm. The speakers were located in the frontal horizontal plane at angles ranging from −90° to +90° relative to the subject, a spacing of 15° was used. The speakers were placed at a distance of 1 m of the subject and were labeled 1 to 13. The target signal was played through one of the 13 speakers using a LYNXONE soundcard and a programmable electronic switch box. This switch box, together with the whole test procedure, is controlled by our test software, referred to as "advanced localization procedure" (ALP). The test operator loads the test into the program and enters the responses of the subject by clicking the appropriate buttons. The full test procedure is stored by the program, together with the calculated performance measures. Two other, YAMAHA CBX-S3 powered speakers were present in the test room to create the noise scenario to evaluate localization performance with the noise reduction system. They were placed at a distance of 1 m from the subject at an angle of −90° to +90° relative to the subject. An illustration of the test setup is given in Fig. 1.

C. Stimuli

Earlier studies show that localization of high and low frequencies rely on different binaural processing strategies. Low frequencies ($f < 1000$ Hz) do not generate a large ILD, because the head shadow effect is small for such wavelengths. When localizing low-frequency sounds, ITD information is primarily used. When the wavelength of a sinusoid is smaller than the diameter of the head, timing information becomes ambiguous. For high frequencies ($f > 1500$ Hz), the localization system is based on ILD information and ITD information of the low-frequency envelope of the signal (Moore, 1997a; Hartmann, 1999). To obtain information about both binaural processing paths, a 200 ms 1/3 octave low-frequency noise band ($fc = 500$ Hz) and a 200-ms 1/3 octave high-frequency noise band were chosen as target stimuli. In the first study with normal hearing subjects, a 200 ms 1/3 octave high-frequency noise band centered at 5000 Hz ($fc = 5000$ Hz) was used. When testing hearing impaired persons, this stimulus proved to be useless due to the inaudibility of the stimulus to some test persons. Therefore, a

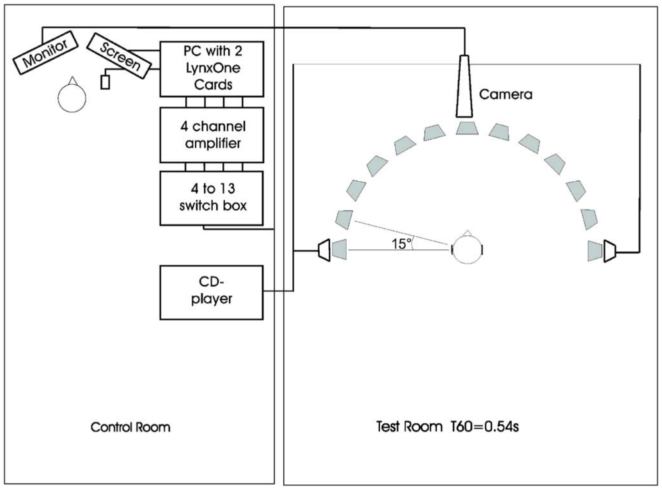

FIG. 1. An overview of the used test setup. The "4 to 13 switch box" is connected to the array of 13 (gray colored) loudspeakers and enables the test program to play target sounds from a personal computer on the speakers (connections are not drawn for reasons of clarity). The compact disk players are connected to the 2 YAMAHA (noncolored) speakers located at ±90° and −90° of the subject. These are used to create the noise scenario. A camera is used to monitor the subject.

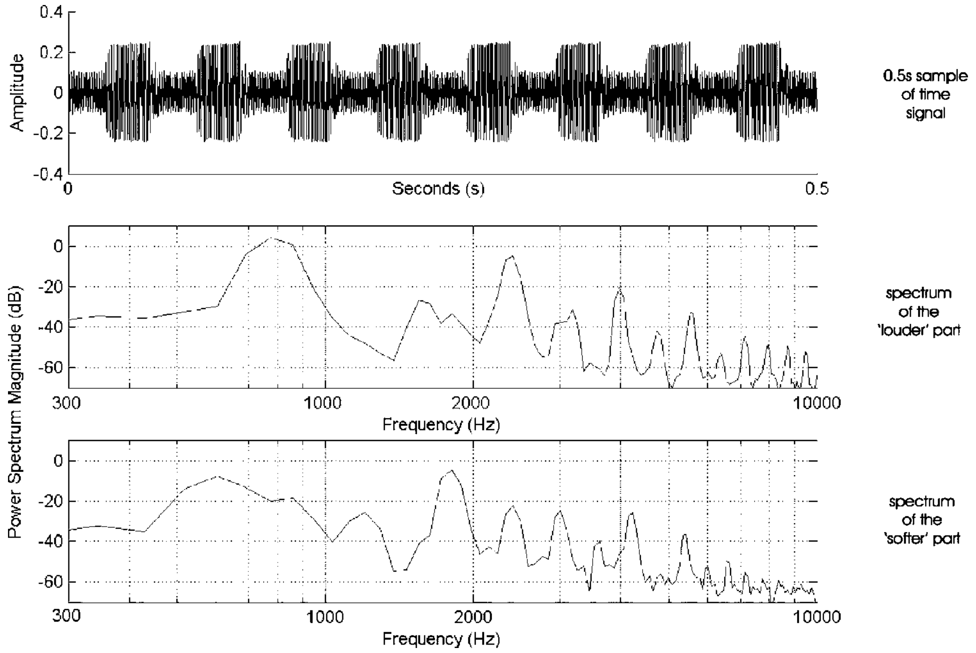

FIG. 2. Up: The time structure of a 0.5 s sample of the used telephone ringing signal which alternates between a "softer" and a "louder" fragment. Middle: The power spectral density of the louder part of the telephone ringing signal. Down: The power spectral density of the softer part of the telephone ringing signal.

200 ms 1/3 octave high-frequency noise band centered at 3150 Hz was used for the hearing impaired subjects. Still, the data of the 5000 Hz test with the normal hearing subjects are given and compared with the 3150 Hz test with the hearing impaired subjects. We believe that this remains a fair comparison for three reasons. First, frequencies are well above 1500 Hz, meaning that the same localization mechanisms are being used. Second, the center frequencies—3150 Hz and 5000 Hz—are separated by less than an octave. Third, the minimum audible angle for frequencies in both stimuli are similar, with the 5000 Hz noise band having a slightly smaller minimal audible angle at the left and right most sides of the head (starting from 60°) (Moore, 1997b) which would give the normal hearing group a slight disadvantage. The third stimulus was a 1 s broadband telephone ringing signal. This is the alerting signal of a telephone, it contains both low and high frequencies and includes a lot of transients which should make localization easier. The time structure and the spectrum of this signal is shown in Fig. 2. An interesting fact is that human subjects are very familiar with and highly trained on localizing a telephone signal in their daily lives.

All target signals are cosine windowed with a rise and fall time of 50 ms. The telephone stimulus was tested in silence, as well as with a multitalker babble source located at the left and the right side of the subject. When tests were carried out with hearing aids or with normal hearing subjects, stimuli were presented at 65 dB SPL. For the noise scenario, the two noise sources were set at 62 dB SPL giving a signal-to-noise ratio (SNR) of 0 dB in the center of the speaker array. Sound level calibrations were done in absence of the subject. To estimate the impact of signal processing in bilateral hearing aids, tests with and without hearing aids are compared. To rule out the effect of audibility, tests were carried out at equal sensation levels with and without hearing aids. The amplification level of the stimuli was corrected until the subject confirmed that an equal sensation level was obtained with and without hearing. Afterwards, the noise level was corrected to keep the SNR of 0 dB. Because of the extra amplification in the unaided condition, the results do not reflect a "daily life" comparison between the aided and unaided condition. However, they should reflect the auditory ability of the subject to use binaural cues.

D. Test protocol

Subjects sat inside the array of 13 speakers and the chair was elevated until the ears reached the level of the 13 speakers. For the first tests with normal hearing (the test with the low- and high-frequency noise band), four repetitions were used per speaker resulting in 52 presented trials per test. Due to lack of time, all the other tests (all tests with the hearing impaired and both tests with the telephone signal for the normal hearing) have three repetitions on each speaker resulting in 39 presented trials per test. The stimuli were presented randomly and were roved with a roving level of 4 dB (between −4 dB and 0 dB). All subjects were instructed to keep their head fixed and pointed to 0° during stimulus playback. They were watched on a monitor. The task was to identify the speaker where the target sound was heard. Hearing aid users were tested without their hearing aids, with their hearing aids using an omnidirectional microphone configuration and with their hearing aids using an adaptive directional microphone configuration. Three different stimuli were used. Two different acoustical scenarios were tested with the broadband stimulus (in silence and with multitalker babble sources). All four test scenarios were performed twice for each test subject. Two sessions were held on different dates for test-retest purposes, and all tests were completed during each session. One subject had one shorter visit in which not all scenarios were tested, combined with a longer session in which some tests were repeated twice. The tests that had to be done twice were performed in the beginning and at the end of the second session. No influence was seen on the test results. One test took about 5 min, and one session including all scenarios took less than 1.5 h. Subjects had a break after every six tests and could take a break whenever they felt tired. In total, 320 individual test runs were completed $(4 \times 4 \times 10 \times 2)$.

E. Performance measures

Different error measures have been used in previous localization studies (Noble and Byrne, 1990; Lorenzi *et al.*, 1999b; Van Hoesel *et al.*, 2002). We will focus on two commonly used error measures:

(1) Root-mean-square (rms) error

$$\text{rms}(^\circ) = \sqrt{\frac{\sum_{i=1}^{n} (\text{stimulus} - \text{response})^2}{n}}, \tag{1}$$

(2) Mean Absolute Error (MAE)

$$\text{MAE}(^\circ) = \frac{\sum_{i=1}^{n} |\text{stimulus} - \text{response}|}{n}, \tag{2}$$

where n is the number of presented stimuli. When using MAE, all errors are weighted equally, while in the rms error large errors have a bigger impact than small errors. The smallest nonzero error a subject can make during one test run equals 2.40° rms and 0.38° MAE (with $n=39$ trials per test run). Statistical analysis has been performed on both error measures, showing similar results. Throughout this manuscript, the data will be reported in detail only using the rms error measure. The mean and standard deviation of the MAE values will be given for the different subject categories for all tested conditions. This gives the reader the opportunity to compare with other work where MAE error measures have been used. Throughout this paper, statistical analysis will be shown only for rms values.

III. RESULTS AND ANALYSIS

First, the data and statistical analysis of the normal hearing persons are presented, followed by the data and analysis of the hearing impaired subjects. The data shown for each subject are the average over test and retest conditions. This is done because no statistical difference is found between test and retest conditions for both the normal hearing and the hearing impaired subjects. All statistical analyses are performed using SPSS 10.0 with test and retest separated in a repeated-measures ANOVA. A standard significance level of 0.05 is used throughout the manuscript. The different test conditions are identified as follows: For the hearing-impaired group, the three hearing aid conditions are: No—without hearing aids; o—with hearing aids with an omnidirectional configuration; and a—with hearing aids with an adaptive directional configuration. The normal hearing group is identified as nh. The stimulus conditions are identified as follows: 500 Hz—1/3 octave low-frequency band; 3150 Hz or 5000 Hz—1/3 octave high-frequency band; ts—wideband telephone signal in silent condition; and tblr—telephone signal with babble jammer on the left and right. The data and statistical analysis will motivate the discussion in Sec. IV.

TABLE II. The individual rms data with the mean MAE and rms data of the normal hearing subjects for the four different test conditions. All data are in units of degrees (°)

rms error (°)	ts	tblr	500 Hz	5000 Hz
TVS	10.5	12.5	14.3	22.9
SB	6.1	12.1	14.4	22.8
SVD	10.4	11.6	15.3	23.1
LD	5.3	13.6	15.8	21.5
LVDP	5.3	9.9	10.5	14.0
KH	3.3	11.6	11.0	16.4
HD	9.9	13.0	14.0	25.4
EBI	4.5	12.0	12.3	21.9
EBO	10.0	11.1	16.4	24.2
DVS	2.4	10.3	11.2	21.0
Mean rms	6.8	11.8	13.5	21.3
stdev	3.1	1.1	2.1	3.5
Mean MAE	3.5	7.3	8.7	14.3
stdev	2.6	0.9	1.9	2.9

Note: stdev=Standard deviation.

A. Normal hearing subjects

The data of the normal hearing subjects are given in Table II and represented in Figs. 3–5. Table II shows the individual rms results and the mean rms and MAE results of the normal hearing subjects. It shows that all normal hearing subjects perform better with the low-frequency narrow-band signal (average rms error: 13.5°) than with the high-frequency narrow-band signal (average rms error: 21.3°).

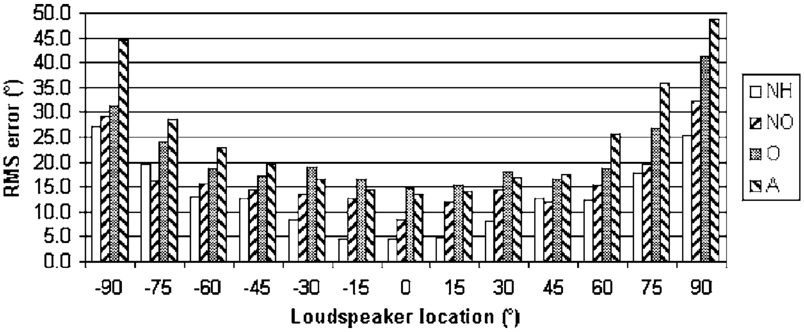

FIG. 3. The error bars show the rms error per speaker when accumulating all responses of the different test conditions per stimulus location. This was done for the group of normal hearing subjects (NH), the group of hearing impaired subjects without hearing aids (NO), with hearing aids using an omnidirectional configuration (O), and an adaptive directional configuration (A).

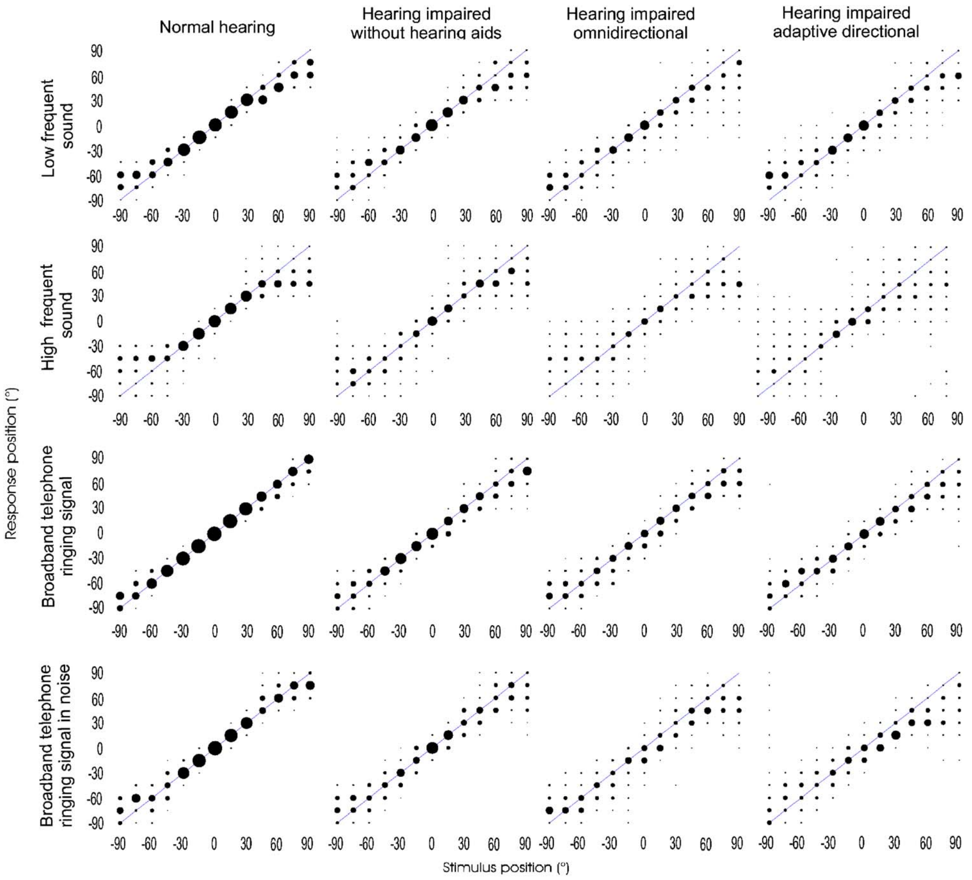

FIG. 4. All responses given by the normal hearing subjects and the hearing impaired subjects with and without hearing aids for the different stimuli and acoustical conditions. The surface of the circles is proportional to the amount of responses given by the subjects.

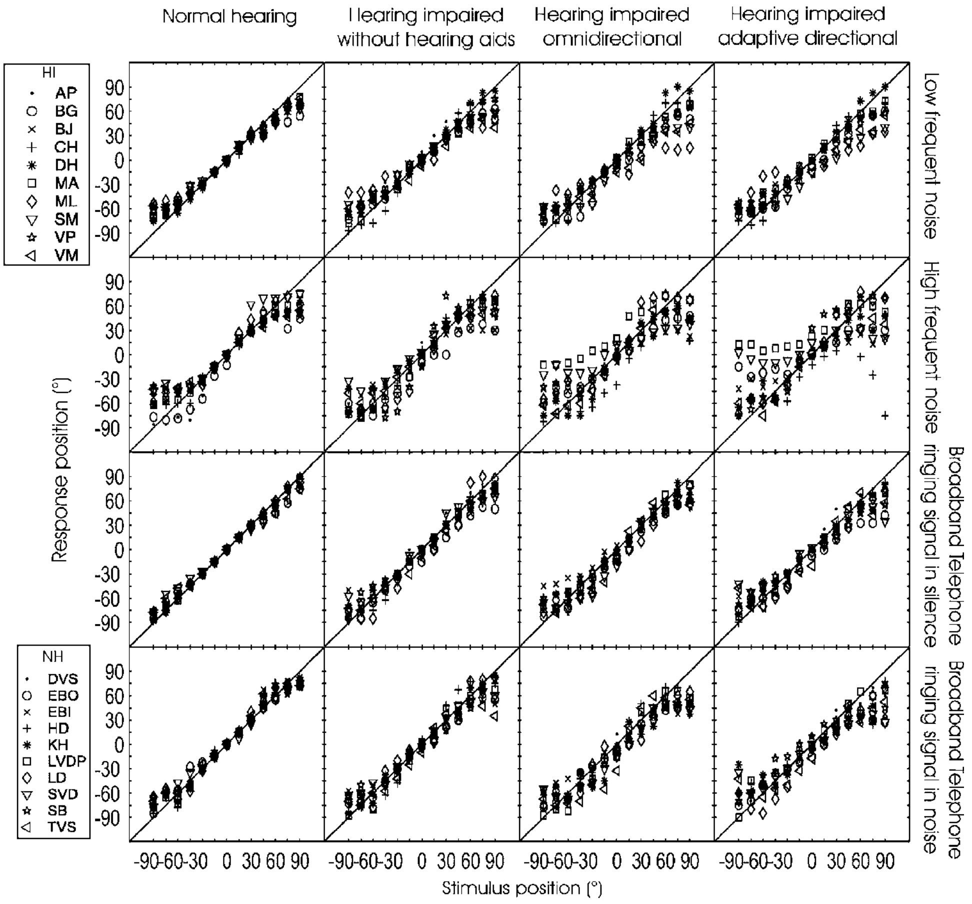

FIG. 5. The mean responses given by the different normal hearing subjects and the different hearing impaired subjects with and without hearing aids for the different stimuli and acoustical conditions.

TABLE III. The individual rms data with the mean rms and MAE data of the hearing impaired subjects for the four different test signals and three different hearing aid settings.

	ts			tblr			500 Hz			3150 Hz		
rms (°)	No HA	Omni	Adapt	No HA	Omni	Adapt	No HA	Omni	Adapt	No HA	Omni	Adapt
AP	12.6	16.5	19.6	14.3	18.3	17.1	16.5	17.3	18.6	21.7	21.3	21.3
BG	18.2	15.6	24.4	15.7	18.4	26.8	14.8	20.2	16.4	28.3	23.4	37.4
BJ	15.3	19.4	16.3	18.0	24.6	26.4	16.8	14.4	16.4	29.3	30.9	35.7
CH	12.1	12.9	8.3	16.6	18.0	28.2	12.4	12.8	14.1	18.2	33.7	61.5
DH	8.1	15.0	10.6	9.7	28.9	31.1	11.6	13.8	13.1	18.2	23.4	22.8
MA	8.5	10.2	12.4	12.1	15.8	14.2	15.8	15.0	15.5	14.3	39.0	49.6
ML	14.6	14.8	15.0	15.4	16.9	19.8	27.1	38.4	35.0	16.9	22.6	18.3
SM	16.2	19.4	25.9	16.3	24.7	31.1	18.7	25.0	27.1	25.0	36.9	47.5
VP	13.3	17.5	17.5	14.4	21.1	25.4	14.5	15.6	18.8	31.9	26.8	29.2
VM	11.0	20.1	24.9	20.8	26.3	29.3	21.3	27.8	26.3	20.3	21.4	26.6
Mean rms	13.0	16.1	17.5	15.3	21.3	25.0	17.0	20.0	20.1	22.4	27.9	35.0
stdev	3.3	3.1	6.2	3.0	4.5	5.9	4.5	8.1	7.1	5.9	6.7	14.1
Mean MAE	8.8	11.7	12.4	10.6	15.9	17.8	12.1	15.1	15.4	16.0	21.4	25.7
stdev	2.9	3.0	5.2	2.5	3.8	4.1	4.2	7.2	7.1	5.2	6.5	10.3

Note: stdev=Standard deviation.

Also, all subjects perform better with the transient broadband signal (average rms error: 6.8°) than with both narrow-band signals. Performance drops for all tested subjects when noise is added to the scenario with the broadband telephone ringing signal (average rms error: 11.8°). These statements are confirmed by a two-way repeated-measures ANOVA (with Bonferroni adjustment for multiple comparisons).

The ANOVA is carried out on the normal hearing data with the factors "test signal" (500 Hz noise band, 5000 Hz noise band, and telephone in silence and telephone with babble from left and right) and "test-retest." A main effect for the factor test signal is observed (lower bound, $p < 0.001$). No main effect was seen for the factor test-retest for the standard 0.05 level (lower bound, $p = 0.330$) and no significant interaction between the two factors was found (lower bound, $p = 0.225$). For the standard 0.05 level, all four different test signals are significantly different from each other (all $p \leqslant 0.003$), except for the 500 Hz and the "telephone with babble" condition ($p = 0.066$).

The data can also be interpreted per angle of incidence. The white error bar in Fig. 3 shows the rms error per speaker when accumulating all responses of the normal hearing subjects over the different test conditions. This illustrates that normal hearing subjects have a very good performance in the most frontal area of the horizontal plane (rms error <10° and >80% correct answers for every angle in the area between −30° and +30°). At the sides, sensitivity drops and localization starts to detoriate. The same tendency can be seen in the left column of Fig. 4, which shows all responses given by the normal hearing subjects under the different test conditions. However, these figures should be interpreted with caution because they represent an accumulation of the responses of the different test subjects on a localization task, which is a subject dependent process. The left column of Fig. 5 illustrates the distribution of the mean response given by each subject for each speaker location and for each test condition. This figure shows that the similarity between the mean responses given by the different normal hearing subjects was relatively high for most test conditions. Only the high-frequency stimulus showed larger dissimilarities, especially at the sides of the head.

B. Hearing impaired subjects

Hearing impaired subjects were tested in the same conditions as the normal hearing except for the fact that the 5000 Hz stimulus was replaced by a 3150 Hz stimulus. All tests were performed with six stimuli in total per condition (three each for test and retest). Figures 3–5 illustrate the data obtained from the hearing impaired subjects. The individual results of the hearing impaired subjects are given in Table III.

A two-way repeated-measures ANOVA (with Bonferroni adjustment for multiple comparisons) was carried out on the hearing impaired data on the factors test signal (500 Hz noise band, 3150 Hz noise band, and telephone in silence and telephone with babble from left and right), "hearing aid" setting (omnidirectional, adaptive directional, and no-hearing aid), and test-retest. A main effect for the factor test signal (lower bound, $p = 0.011$) and the factor hearing aid setting (lower bound, $p = 0.001$) is observed. No main effect is observed for the factor test-retest (lower bound, $p = 0.095$). No significant interactions are found at the standard 0.05 significance level (test signal*hearing aid setting, lower bound, $p = 0.185$; test signal*retest, lower bound, $p = 0.487$; hearing aid setting*retest, lower bound, $p = 0.209$, and hearing aid setting*test signal*retest, lower bound, $p = 0.414$). Pairwise comparisons for the factor hearing aid setting show a significantly better performance without hearing aids (no) compared to both conditions with hearing aids. No significant difference at the standard 0.05 level was found between the omnidirectional (o) and adaptive directional condition (a) although the p value is very close to the 0.05 bound (p

TABLE IV. p values (with Bonferroni adjustment) of the pairwise comparison for hearing impaired subjects. Conditions without hearing aids (no), with hearing aids with an omnidirectional microphone (o), and with hearing aids with an adaptive directional microphone (a) are compared with each other (*=significant for a significance level of 0.05).

	45°/−45°	±60°/±90°	Full
General (Four conditions)			
no vs o	0.038^{*}	0.002^{*}	0.002^{*}
no vs a	0.014^{*}	0.001^{*}	0.001^{*}
o vs a	0.998	0.046^{*}	0.053
500 Hz			
no vs o	0.092	0.371	0.133
no vs a	0.320	0.040^{*}	0.032^{*}
o vs a	0.625	1.000	1.000
3150 Hz			
no vs o	1.000	0.105	0.284
no vs a	0.441	0.071	0.098
o vs a	1.000	0.333	0.120
ts			
no vs o	0.014^{*}	0.227	0.046^{*}
no vs a	0.060	0.095	0.059
o vs a	1.000	0.637	1.000
tblr			
no vs o	0.038^{*}	0.004^{*}	0.016^{*}
no vs a	0.012^{*}	0.084	0.002^{*}
o vs a	0.458	0.009^{*}	0.044^{*}

$=0.053$). The p values of all pairwise comparisons are summarized in the column "Full" of Table IV. Because the assumption was made that the two main horizontal localization mechanisms (ITD and ILD) have a different contribution to the localization performance with the different stimuli, a separate analysis on each signal is done for the hearing impaired group. This could give better insight into the distortion of cues by hearing aids. For each signal, a repeated-measures ANOVA is performed with the factors hearing aid setting (no-hearing aid, omnidirectional, and adaptive directional) and test-retest. Each time a Bonferroni adjustment was used for multiple comparisons. The p values of the pairwise comparisons discussed below are summarized in the column labeled Full of Table IV.

The low-frequency noise band. There is a main effect for the factor hearing aid setting (lower bound, $p=0.037$). No interaction with the factor 'test-retest' is observed ($p=0.310$). The setup without hearing aids outperformed the setup with the adaptive directional microphone significantly (on average by 3.1°). Although the mean difference between the omnidirectional configuration and the no-hearing-aid condition is 3.0°, no significant difference for the standard 0.05 level is found between these conditions. The mean performance of the omnidirectional and adaptive directional configuration was very similar for this test signal. No significant difference between these conditions is observed.

High-frequency noise band. There is a main effect for the factor hearing aid setting (lower bound, $p=0.042$). No interaction is observed (lower bound, $p=0.202$). Large differences in the mean results between the different conditions are observed; however, no significant differences are found in the pairwise comparisons.

Broadband telephone ringing signal in silence. There is a main effect for the factor hearing aid setting (lower bound, $p=0.043$). No interaction is observed (lower bound, $p=0.289$). The no-hearing-aid condition is significantly better than the omnidirectional condition (on average 3.1°). No significant difference is found between the no-hearing-aid and adaptive directional condition for the standard 0.05 level, although the p value lies close to the level of significance ($p=0.059$). No difference is found between the omnidirectional and adaptive directional condition ($p=1$).

Broadband telephone ringing signal with babble from left and right. A main effect is found for the factor hearing aid setting (lower bound, $p=0.002$). No interaction is observed (lower bound, $p=0.509$). Statistical significant differences are found in all pairwise comparisons, with the no-hearing-aid condition performing better than both hearing aid conditions (on average 6.0° and 9.7°), and the omnidirectional configuration performing better than the adaptive directional configuration (on average 3.7°).

Another aspect that seems to make a distinction between the data obtained with the adaptive directional microphone configuration and the other configurations is the presence of left-right confusions for the extreme left and right angles (Fig. 4). Several subjects experienced this problem for stimuli presented at ±90° when they were tested with the adaptive directional microphone. This was found for the high-frequency noise band (subjects SM, MA, VM, and CH) and for the telephone signal in noise (subjects DH, VM, CH, and BG).

An evaluation per angle of incidence is shown in Fig. 3. This shows the rms error per speaker location when accumulating the responses of the hearing impaired subjects on the different stimulus conditions, and was done for the three different hearing aid conditions (omnidirectional, adaptive directional, and without hearing aids). Figures 3 and 4 illustrate that hearing impaired subjects have a better localization performance in the frontal region compared to the region at the sides of the head, which is in agreement with the data of the normal hearing subjects. However, it is important to note that when using hearing aids, a decrease in performance is observed not only at the sides of the head, but also in front of the listener. These figures should be interpreted with caution. They represent an accumulation of the responses given by the different hearing impaired subjects on a localization task, which is a subject dependent process. A large intersubject variance is present in the hearing impaired data, especially with hearing aids. This is illustrated in Fig. 5, which gives the mean response of each subject on each stimulus location for each test condition.

C. Hearing impaired without hearing aids versus normal hearing

When evaluating the normal hearing and the hearing impaired subjects, one can clearly see differences in performance (Table II versus Table III, Fig. 3–5. In this section, the data of the normal hearing group are compared with the best condition of the hearing impaired group, being the condition without hearing aids. The data of all four test signals (low-frequency, high-frequency, telephone ringing signal, and telephone ringing signal in noise) are included in a repeated-measures ANOVA. A between-subjects factor—subjects—is introduced which separates the group of normal hearing and hearing impaired persons. There is a main effect present for the factor test signal (lower bound $p < 0.001$) and no effect is found for the factor test-retest. No interactions are found (signal*subjects, lower bound $p = 0.129$, signal*retest, lower bound $p = 0.214$, and signal*retest*subjects, lower bound $p = 0.182$). The group of normal hearing subjects perform better than the hearing impaired group without hearing aids ($p = 0.005$). This can also be seen when comparing the data of the normal hearing and the hearing impaired in Figs. 3 and 4. The pairwise comparisons of the factor test signal show the same results as described in the normal hearing section. There is a better performance when using the broadband stimulus compared to both narrow-band stimuli ($p < 0.001$ for both the low- and high-frequency stimulus) and compared to the broadband stimulus in noise ($p = 0.001$). There is also a better performance when using the low-frequency stimulus compared to the high-frequency stimulus ($p < 0.001$). Another difference between the normal hearing and the hearing impaired subjects is the larger consistency between the different subjects in the normal hearing group compared to the hearing impaired group (Fig. 5).

IV. DISCUSSION

Three research questions were raised in the introduction of this manuscript. The results and analyses from the previous section will be used to answer these questions.

A. Normal hearing and hearing impaired performance

Section III describes and quantifies the localization performance of normal hearing and hearing impaired subjects in the frontal horizontal plane. Hearing impaired subjects were tested in three different conditions: Without their hearing aids (no), with hearing aids with an omnidirectional microphone configuration (o), and with hearing aids with an adaptive directional microphone configuration (a). Overall, the average performance with the low-frequency stimulus (mainly ITD) was better than performance with the high-frequency (mainly ILD) stimulus (Secs. III A and III C). Test results improved when using the broadband stimulus compared to high- or low-frequency stimuli. This can be explained by the possibility to use both ILD and ITD cues and by the time structure of the broadband signal. The length of the stimulus could also have affected localization performance. When using a 1 s signal, slight head movements can occur during stimulus playback which would give the subject an extra advantage. When adding jammer sources with a SNR of 0 dB, performance drops significantly for both the hearing impaired subjects and the normal hearing subjects. This confirms the results of the study of Lorenzi *et al.* (1999b).

Statistical analysis (Sec. III C) showed a better performance of the normal hearing subjects compared to the hearing impaired subjects (Sec. III C Figs. 3 and 4). Although the two subject groups were not age matched, 64% of the individual scores of the hearing impaired subjects without hearing aids are within two standard deviations, and 39% are within one standard deviation of the results of the normal hearing group (when comparing the data of the same test conditions). In the study of Lorenzi *et al.* (1999a), it was also mentioned that a considerable percentage of the hearing impaired subjects (between two and three subjects out of four) can reach normal hearing performance on a binaural task. This leads us to conclude that some hearing impaired subjects are able to use binaural cues which is important to motivate further research on binaural signal processing for hearing aids.

It was also shown that for both the normal hearing as the hearing impaired subjects, localization is more accurate in front of the listener than at the left and right side of the listener (Figs. 3 and 4) which agrees with the data of Makous and Middlebrooks (1990) and Carlile *et al.* (1997). However, in these studies, the decrease in accuracy at the sides of the head was less pronounced which might be explained by the difference in the experimental setup. The hearing impaired subjects, who were using their own hearing aids, and are therefore highly trained on localizing sound sources with these devices in their daily lives, were not able to localize half of the targets correctly in the most frontal region (from −45° to +45°), whereas normal hearing subjects have a near 100% score in this region (Secs. III B and III A).

B. Do bilateral hearing aids preserve localization cues?

To answer this question, tests were performed with hearing impaired subjects with and without hearing aids. By using equal sensation levels (for restoring audibility), a comparison can be made between performance when all binaural information is present and performance with hearing aids. Throughout the different tests, four out of eight comparisons between unaided and aided conditions showed significant better performance unaided than aided for a significance level of $p = 0.05$ (and six out of eight for a significance level of $p = 0.1$) (see Table IV). A general analysis confirmed that performance without hearing aids is significantly better than with hearing aids (Sec. III B). This can be related to the data of Noble *et al.* (1998) and Byrne *et al.* (1998) obtained with open earmolds, allowing the subjects to use binaural cues of the direct sound instead of the output of the hearing aid. Moreover, when comparing with normal hearing performance, only 36% of the individual test results with hearing aids fall within 2 standard deviations of the results of the normal hearing subjects, and only 20% of the individual test results fall within 1 standard deviation of the results of the normal hearing subjects. These percentages are considerably smaller than the numbers shown in the previous section for the hearing impaired subjects without hearing aids. This confirms that hearing aid users localize better without their hearing aids than with their hearing aids.

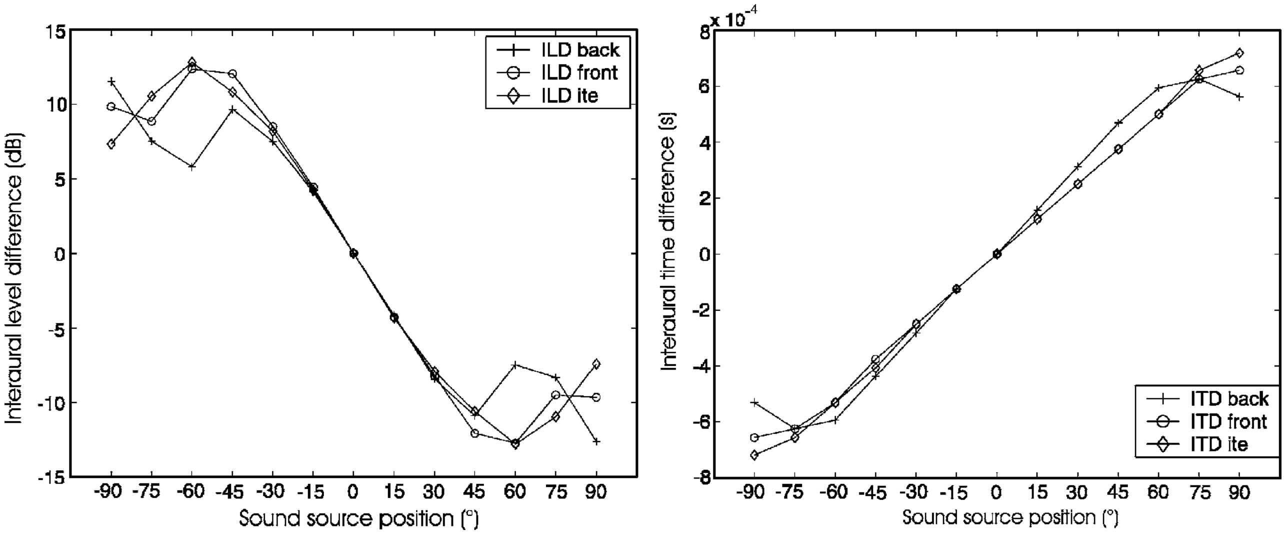

FIG. 6. ITD and ILD measurements with two Canta7 BTE hearing aids prototypes on a CORTEX manikin in anechoic conditions. Interaural time and level differences were measured between the ITE microphones of a CORTEX manikin (ITD ite, ILD ite), between the front omnidirectional microphones of the BTE devices (ITD front and ILD front), and between the back omnidirectional microphones of the BTE devices (ITD back and ILD back). Measurements were made using a broadband white-noise stimulus.

Extra measurements were made to quantify the influence of microphone position on interaural cues. On a BTE hearing aid, the microphones are positioned relatively far from the eardrum, which may influence the interaural cues given to the listener. One could assume that this is the reason for the degradation in horizontal localization performance. To quantify this influence, physical measurements are made using the microphones of BTE hearing aid devices and in the ear microphones (ITE) of a manikin under anechoic conditions. A 01 dB CORTEX MK2 manikin, a dummy head with torso built according to the IEC 959 standard, is used with two G.R.A.S. IEC 711 ear simulators. A G.R.A.S. 40AG pressure microphone is located in each ear simulator. The BTE devices are two Canta7 dual microphone shells with direct microphone outputs. All recordings are made using an eight-channel G.R.A.S. 12AG preamplifier and two synchronized LYNXONE soundcards with a sampling rate of 48 kHz. A broadband white-noise signal is recorded simultaneously with all six microphones (two CORTEX MK2 in the ear and four BTE microphones). ITDs and ILDs are calculated between the two ITE microphones of the manikin the two omnidirectional microphones located at the front of the BTE devices and between the two omnidirectional microphones located at the back of the BTE devices.

The measured ITDs are calculated using a cross correlation function and are given in the left part of Fig. 6. This illustrates that the ITDs between the BTE microphone pairs do not fully agree with the data of the ITE microphone pair, which represents the ITD information at the eardrums of a human listener. Moreover, the distortion is dependent on the microphone placement on the BTE. The front microphone pair shows a distortion of ITD information only around −90° and +90°. The back microphone pair shows larger distortions and generates almost similar ITDs for the area from −60° to −90° and from 60° to 90° which could have an effect on localization performance. These measurements were done using a broadband white-noise. Interaural cues are, however, to some extent frequency dependent (Blauert, 1997 and Kuhn, 1977). A frequency specific analysis was done to get a clear comparison between the interaural measurements and the localization measurements described earlier. These analyses made clear that most of the ITD distortion shown in Fig. 6 (at angles beyond ±60°) is generated by relatively high frequencies ($f > 1$ kHZ). Lower frequencies showed smaller differences between the ITE and BTE measurements, but showed the same tendency as the broadband measures shown in Fig. 6 with the front microphone pair having a smaller influence on the ITD information (<40 μs ITD distortion over all angles) compared to the back microphone pair and with the back microphones producing almost similar ITDs for the angles at the most left and right side of the head.

The right part of Fig. 6 shows the ILD cues generated by a broadband white-noise stimulus. The distortion generated by the back microphone pair is again more pronounced than the distortion by the front microphone pair, and is mainly located at the most left and right angles. The measured ILDs for low frequencies are much smaller (less than 7 dB for frequencies below 1000 Hz). For these frequencies, the measured maximum distortion relative to the ITE condition was <1.5 dB for the front microphone pair and <3 dB for the back microphone pair over all angles. For higher frequencies (>1 kHz and <5 kHz), the measured ILDs were much larger (maximum: 17 dB). Only at the sides of the head (starting from ±60°) were the high-frequency ILDs measured at the front BTE microphones very different than the ILDs generated by the ITE microphones (maximum measured difference around 7 dB at an angle of 75°). The back microphones showed larger deviations than the front microphones, especially at the sides of the head (>5 dB difference at the sides of the head starting from ±45° with a maximum difference of 8 dB at 75°).

In general, both ITD and ILD distortions are relatively small, especially if one would assume that the hearing aid manufacturer uses the front microphone as the reference microphone. To rule out the effect of microphone placement, the data were split into two parts: The data of the area where the impact of the microphone position is almost negligible (from −45° to 45°) and the remaining data for which the distortion could be (although unlikely) generated by the microphone position. The statistical analysis of Sec. III was repeated for these two subareas, the p values of the pairwise comparisons are summarized in Table IV. This table shows that—for the telephone ringing signal in silence and for the telephone signal in noise—performance of the subjects with hearing aids is already significantly lower than without hearing aids for a standard 0.05 significance level. A general analysis of the four test conditions confirms that performance in the area between −45° and 45° is already worse with than without hearing aids. This suggests that the drop in localization performance cannot be explained only by microphone positioning. Moreover, it can be linked to the work of Noble and Byrne (1990) (see Sec. I) where no significant differences in localization performance were found when comparing BTE, ITE, and ITC hearing aids. Because microphone positioning seems insufficient to explain the difference in localization performance, the data strongly suggest that the signal processing of hearing aids introduces interaural cue distortion when used in a bilateral hearing aid configuration. Further, more fundamental research is needed on the separate signal processing blocks of an hearing aid to pinpoint the exact blocks that cause the interaural distortion which could lead to a better design of hearing aids for bilateral hearing impaired subjects.

C. Can noise reduction systems have an influence on localization performance?

Although most test scenarios in this study do not show a significant difference between the adaptive directional microphone configuration and the omnidirectional microphone configuration (Table IV), a trend of the omnidirectional microphone configuration performing better than the adaptive directional microphone configuration can be observed in most test conditions (Table III and Fig. 4). Analysis showed that the overall effect was not significant (but close to significance) for a significance level of $p=0.05$ ($p=0.053$). However, the adaptive directional microphone is significantly different from the omnidirectional microphone configuration when directional noise is added at ±90° ($p=0.044$) (Table IV). The adaptive directionality has a negative impact only in this test condition, probably because the noise sources were playing continuously throughout this test. Therefore, the noise reduction system had plenty of time to adapt to a steady filtering operation. In the other tests, very short sounds were used which could have given the noise reduction system not enough time to adapt to a steady filtering operation. Two reasons might explain the negative affect of the adaptive directional microphone. First, an adaptive directional microphone creates a directional pattern depending on the noise scenario. It searches for the most dominant noise source (normally the search area is restricted to the rear horizontal plane) and puts a null in this direction. When testing with babble jammer sources at the left and right side of the subject, the adaptive directional microphone will try to cancel out these directions. It can be assumed that the ILD perception of the stimulus, around ±90°, could be degraded by this filtering operation. This would explain why the difference between the omnidirectional and the adaptive directional microphone configuration is only significant in the area from 60° to 90° and not in the area from −45° to 45° (Table IV, general analysis, and tblr analysis). Second, the directional filter introduces a phase relationship between the input and output of the hearing aid. ITDs would be distorted if left and right hearing aids have a different phase relationship. These are two suggestions and further research is needed to clarify why an adaptive directional microphone affects localization performance. However, the results of the tests indicate that a noise reduction system can have an influence on binaural cues. Therefore, when designing noise reduction systems for hearing aids, more attention should be given to bilateral usage, in general, and more specifically to the preservation of interaural cues.

To get a better insight on the type of interaural distortion experienced by hearing aid users (ITD or ILD), low- and high-frequency stimuli were used. When comparing the omnidirectional condition with the condition without hearing aids in Table III, it shows that four out of ten subjects have a large decrease in performance for the 500 Hz stimulus when using hearing aids (subjects BG, ML, SM, and VM) which could indicate distortion of time cues by the hearing aids. On the other hand, five subjects out of ten show a large decrease in performance for the 3150 Hz stimulus (subjects CH, DH, MA, ML, and SM) which could indicate distortion of level cues. So, some subjects seem to experience problems with level cues, some with time cues, and some do not experience problems at all when localizing a high- and low-frequency stimulus with an omnidirectional configuration (e.g., subject AP). Strangely enough, subject AP, who had no decrease in performance with both low- and high-frequency stimuli did show a decrease in performance with the transient broadband signal and the broadband signal with jammer sounds. When comparing the omnidirectional with the adaptive directional microphone configuration in Table III, it shows that only small differences are present for the 500 Hz stimulus, but that large differences are present for the 3150 Hz stimulus for five out of ten subjects (subjects BG, BJ, CH, MA, and SM). This could indicate that, for these subjects, the extra distortion given by an adaptive directional microphone is mainly ILD distortion. However, these analyses should be interpreted with the necessary caution. The reader should pay attention to the fact that these systems are multiband processing devices. Different subbands can be processed inside the hearing aid in a different way. This would not only lead to the possibility of interaural cue distortion, but also to the possibility of generating interfering interaural cues over the different frequency channels. How the auditory system of the different subjects would react to these interfering cues is an unknown factor when interpreting the data. Therefore, caution is advised when extrapolating data of narrow-band signals to broadband signals. Also, no attention has been given to spectral cues. It is known that high frequency spectral cues improve localization performance and are especially useful for vertical localization and for resolving front-back confusions. The influence of spectral cues was not studied but can be assumed to be limited because of the nature of the task (no front-back ambiguities or vertical localization), the high-frequency loss of the subjects, and the limited frequency bandwidth at the output of BTE hearing aids. Monaural spectral enhancement techniques were switched off in this study which might influence (enhance or degrade) localization performance in real-life situations.

V. CONCLUSIONS

Three research questions are addressed in this paper. First, the localization performance of normal hearing and hearing impaired subjects in the frontal horizontal plane is quantified. The group of hearing impaired subjects localized sounds less accurately than the normal hearing subjects. However, it is shown that the hearing impaired subjects can still use binaural cues which motivates further research on binaural hearing aid systems. Second, current state of the art bilateral hearing aids have a negative impact on binaural cues, thereby degrading localization performance. The decrease in localization performance with hearing aids could not be fully explained by microphone placement which indicates that the different signal processing blocks inside a hearing aid distort interaural cues. More fundamental research should be done on these separate building blocks. Third, noise reduction techniques, such as an adaptive directional microphone, can have an additional significant negative impact on localization performance. Whether a significant drop in localization performance occurred with the noise reduction technique depended on the stimulus and noise scenario used in the localization test. The fact that hearing aid users receive distorted binaural cues could lead to degraded speech perception in noisy listening situations, in which binaural cues are important. The main conclusion seems to be that using two monaural hearing aids is a suboptimal solution for a bilateral hearing aid user. More research should be done on preserving binaural acoustical cues in noise reduction algorithms and hearing aids, in general.

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