Sound localization with and without hearing aids

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Introduction

Building a realistic spatial representation of our surrounding environment is an important task of our auditory system. This allows us to localize sounds and to understand speech in adverse scenarios [4],[5]. An inaccurate spatial map will degrade localization and speech perception and will lead to an unnatural perception of sounds. The psycho-acoustical mechanisms used to localize sound sources are fairly well known [6]. The human auditory system mainly uses interaural cues such as interaural level differences (ILDs) and interaural time differences (ITDs) [7, 8] to localize sounds in the horizontal hemisphere. However, sound sources positioned in the front and the back hemisphere generate almost identical interaural properties when they are positioned on the so called cone of confusion. Therefore the auditory system relies on the spectral filtering of the head, torso and especially pinna to resolve the front-back confusions [9, 10]. Each human listener possesses two highly personalized pinnae. The cavities of the pinna reflect and diffract a sound wave dependent on the angle of arrival of the signal. This can be used to resolve front-back confusions and to localize sounds in the vertical plane.

The question whether hearing aids preserve or transmit enough binaural cues to the hearing aid user and whether hearing aid users are still capable of using these cues has been gaining a lot of interest recently [11] [12]. This is partly due to recent technology which enabled the design of binaural hearing aids in which binaural cues may be controlled and preserved. However, the question whether monaural spectral information is preserved by different hearing aids has been studied to a lesser extent. Still some attention has been given to the question whether a natural microphone positioning, such as used in in-the-canal (ITC) hearing aids, has a benefit in terms of preserving monaural and binaural cues. Results of these studies, done more than a decade ago, have been conflicting. Studies such as [2] and [3] found no significant benefit of having a microphone in the ear compared to behind the ear, while [1] did claim a benefit of microphone position. In [3], these differences were explained by difference in test setup since all three studies investigated different dimensions of sound localization simultaneously leading to results which are hard to compare.

Three different dimensions of sound localization are discussed in this manuscript: localization in the frontal horizontal hemisphere, localization in the frontal vertical plane and the ability to resolve front-back confusions. The localization experiment in the frontal horizontal hemisphere is dominated by the processing of binaural cues. The two other dimensions are known to be dominated by the processing of monaural spectral information. Several hearing aids were evaluated: behind-the-ear (BTE), in-the-ear (ITE), but also a newly designed in-the-pinna (ITP) hearing aid. This new hearing aid, i.e. the Be hearing aid, released by GN Resound, uses a flexible positioning mechanism which positions its microphone in the anthelix of the pinna of the hearing impaired subjects. This should give benefits in terms of wind noise reduction and naturalness of sounds. This has renewed the interest in studying the effect of microphone positioning on the monaural spectral cues and on sound localization performance.

Evaluation

Methods

Tests were carried out in a room with a reverberation time of $T_{60} = 0.61s$. For left-right localization, test subjects were placed inside a horizontal array of 13 loudspeakers. The array is illustrated in Figure 1. Speakers were located from -90°(at the left side of the subject) to 90°(at the right side of the subject), with a spacing of 15°and were labelled 1 to 13. For the front-back localization task, listeners were turned side-on to the array, with their right ear facing the array of speakers. A resolution of 30°was used during this experiment by using only the 7 odd numbered loudspeakers. Subjects were seated in a vertical array of loudspeakers during vertical plane localization. Ten speakers were placed at 1m distance of the subject from -45°to 90°with a spacing of 15°. The speaker placed at 0°was located in the horizontal plane while the speaker at 90°was located directly above the subject. During all tests a roving level of 6dB was used to avoid the use of loudness cues. All experiments were done in a test-retest configuration. At present, no significant difference between test and retest has been found for all tests.

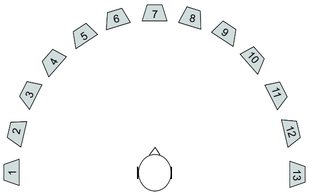

Figure 1: The speaker array used for left-right and front-back localization.

7 hearing impaired subjects were evaluated using different hearing aids. These subjects were used to wearing behind-the-ear (BTE) hearing aids in daily live. The hearing impaired subjects were fitted with GN ReSound

in-the-canal Canta7 or Azure (ITC), GN Resound Be in-the-pinna (ITP), GN Resound Air BTE (BTE-A) and Oticon XW Epoq receiver in the ear, BTE hearing aids (BTE-E). The left-right communication link of the BTE-E was switched on and all optional noise reduction schemes were switched off. An unaided condition, in which the stimuli were compensated for audibility was added to the protocol as a reference. The latter condition was currently only completed for the left-right localization task. The audibility correction was done by using the half gain rule to amplify the stimulus per octave band.

Left-right

First, left-right localization in the frontal horizontal plane was studied. Three stimuli were presented to the subjects: a broadband steady state noise with an average spectrum of a dutch male talker (VU-noise, [13]), a 1/3rd octave noise band centered around 500Hz and a 1/3rd octave noise band centered around 3150Hz. A summary of the data is presented in Figure 2. Since [11] studied localization with normal hearing (NH) subject and hearing impaired (HI) subjects with bilateral hearing aids in very similar conditions, these data were added to the figure (last 3 bars).

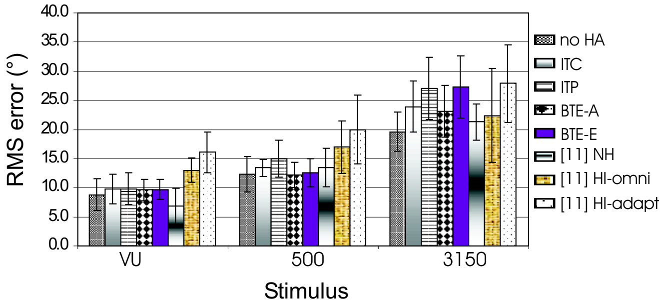

Figure 2: Average RMS errors and group standard deviations from the left-right localization experiment. The data obtained in [11] in similar conditions are also added to the figure.

First, it was observed that broadband stimuli were much easier localized than narrowband stimuli. Using only low-frequency cues led to a better localization performance when compared to using only high-frequency information. It can be assumed that the first condition (500Hz) is dominated by binaural processing of ITDs while the second condition (3150Hz) is dominated by the processing of ILD information. When presenting both ITD and ILD information, localization accuracy improved significantly (VU-stimulus). Second, and probably most importantly is the fact that when comparing the unaided with the aided conditions, averaged over all stimuli, only the BTE-A condition shows no difference with the unaided performance. All the other hearing aids introduced a small but significant degradation in left-right localization. The observed differences are especially prominent when localizing the high-frequency sound. No significant differences were found between hearing aids although a general trend is found that localization with the BTE-A hearing aids was more accurately than with the other hearing aid systems.

These conclusions are very similar to the work presented in [11] and in [12]. In these studies it was found that hearing aids introduce a small but significant degradation in sound localization in the horizontal plane. This degradation becomes significantly larger when switching on additional algorithms such as an adaptive directional microphone.

Front-back

Since, broadband information is needed to distinguish the front from the back hemisphere, front-back experiments were only performed with the broadband vu stimulus. 6 repetitions were used per loudspeaker leading to 42 presentations per test. The accumulated results of the hearing aid users are presented in Figure 3.

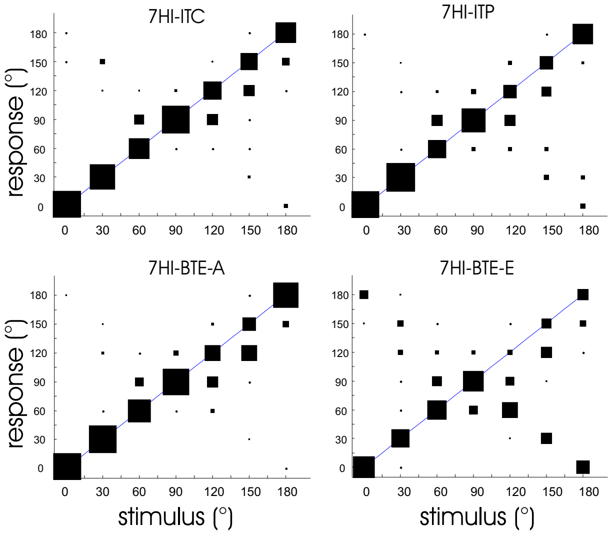

Figure 3: Accumulation of responses (y-axis) given by the group of hearing impaired subjects wearing different types of hearing aids (N=7).

As shown in Figure 3, the results obtained with the different hearing aid systems were surprisingly good except for the BTE-E condition. An error score of 8%±9, 11%±14, 4%±7 and 30%±8 was obtained when using ITC, ITP, BTE-A and BTE-E hearing aids respectively.

To identify the amount of spectral cues, generated by each hearing aid, objective measurements were performed. First, a CORTEX MK2 manikin was fitted with the different hearing aids. Afterwards the stimulus was played from all the different loudspeakers and the sound arriving at the eardrums of the manikin were recorded. Then the spectra of these recordings were calculated and normalized with respect to its overall RMS level. This way, loudness cues were removed from the recordings. To visualize the information which could be used to distinguish the front from the back (in this case 30°from 150°), the spectra of these angles were subtracted and the absolute value was taken. This shows the spectral information which could be used by a listener to discriminate 30°from 150°or the front from the back. The result of this procedure is shown in Figure 4.

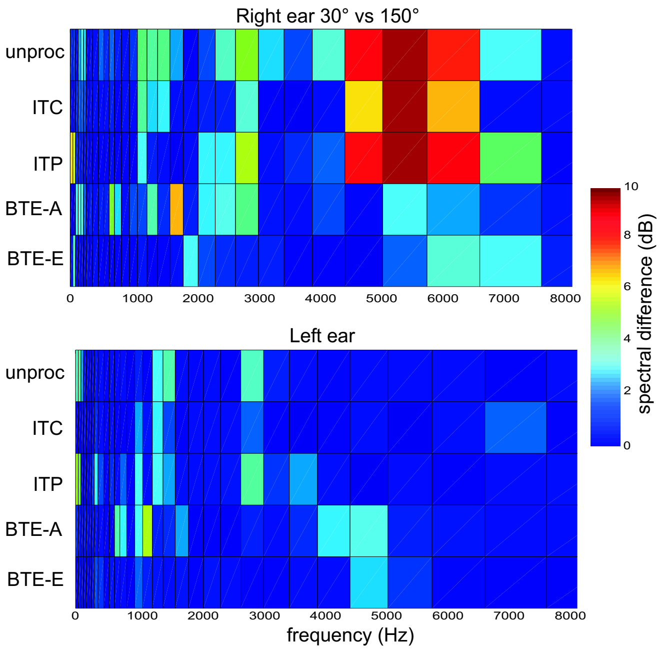

Figure 4: The spectral information present in each hearing aid system to distinguish 30°from 150°.

In this figure, it is observed that especially the right ear, which is the ear facing the loudspeakers, receives spectral information to distinguish 30°from 150°. When comparing the ITC and ITP hearing aids with the unprocessed condition, it is observed that these device almost preserve all spectral information. Both BTE hearing aids however, do not preserve the spectral information. This can be explained by the fact that the microphone of a BTE hearing aid is positioned on top of the pinna instead of close to the eardrum. Still, it is observed that the BTE-A hearing aid preserves some spectral information (between 2 and 3kHZ) while the BTE-E hearing aid removes almost all information. The perceptual evaluation shows that the little information preserved by the BTE-A seemed to be sufficient for the hearing impaired subjects to distinguish the front from the back while performance dropped significantly when using the BTE-E. It should be noted that Figure 4 illustrates the potential present in the different hearing aids. The hearing aid should produce enough amplification in all frequency regions such that the spectral information can be used by the hearing impaired user. Combining the good perceptual performance obtained with the BTE-A hearing aid and the spectral measurements suggests that although positioning a microphone on top of the pinna reduces spectral information, it is not necessarily the main limiting factor with respect to front-back localization.

Elevation

The same group of hearing aid users were evaluated on their capability to localize sounds in the frontal vertical plane. Again the broadband noise was used. An accumulation of the results is given in Figure 5.

Figure 5 illustrates that the differences between the different groups are relatively small. Averaged over all subjects, an RMS error score of 23.2±4.4, 27.5±7.0, 30.1±9.0 and 27.8±5.7 was obtained by the hearing aid users with ITC, ITP, BTE-A and BTE-E hearing aids respectively.

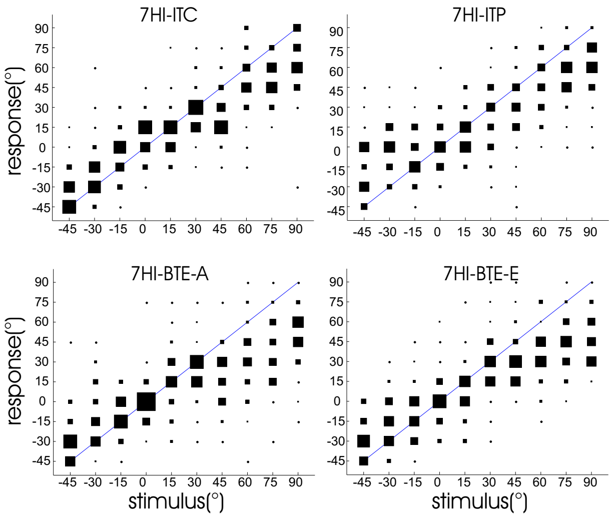

Figure 5: Accumulation of responses (y-axis) given by the group of hearing aid users (N=7) wearing different types of hearing aids on the elevation task.

To quantify the amount of spectral cues preserved or generated by each hearing aid, spectra were measured using a CORTEX MK2 manikin in a similar way as discussed during the front-back experiment. Each spectrum was normalized with respect to its own average RMS level and with respect to 90°. This way, overall loudness cues were removed from the spectrum and a figure is created which illustrates the spectral information which could be used to distinguish an angle x from 90°in elevation. The spectral information generated by the different hearing aid configurations for an angle of 0°are shown in Figure 6. Due to the symmetric test setup, measurements performed with the left and the right hearing aid were similar. Therefore, only the measurements at the right ear are shown.

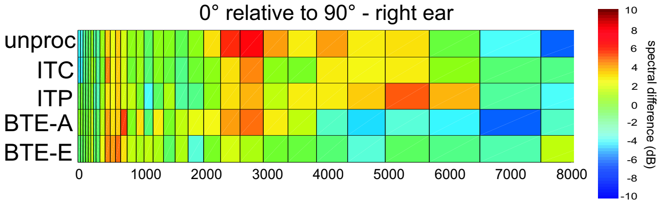

Figure 6: The spectral information present in each hearing aid system to identify 0°of elevation. The spectra are normalized with respect to their own average RMS to remove overall loudness cues and with respect to 90°.

Figure 6 shows that although large variations are present between the recorded spectra, all hearing aids are capable of generating useful elevation cues. This corresponds to the perceptual data in which no large differences were found between hearing aids. The measured spectra show that especially the region between 2 and 3kHz is well preserved by all systems. This is the same region which was well preserved by most hearing aids when analyzing the front-back spectra (Figure 4). In [10], it was shown that this region is dominated by the spectral filtering of head and torso. Moreover, they could demonstrate that normal hearing subjects could be trained to localize sounds in the vertical plane by only using this kind of filtering. It can be assumed that hearing impaired subjects, used to wearing a BTE hearing aid and used to listening to low frequency dominated sounds (since a sloping hearing loss is the most common type of hearing loss) have been highly trained on using this kind filtering.

Conclusion

This manuscript presents a study on sound localization by hearing impaired subjects in three different dimensions: left-right localization in the frontal horizontal plane, front-back discrimination in the horizontal plane and elevation. The first dimension is dominated by the processing of binaural cues while the other two are dominated by the processing of monaural spectral cues. This document shows that hearing aids can affect localization performance. Evidence was found of a reduced left-right accuracy and a reduced ability to resolve front-back confusions when using some of the hearing aids. Although microphone position has a very high impact on the spectral cues crucial to separate the front from the back hemisphere it is not necessarily the main limiting factor. This is probably due to the fact that hearing impaired subjects are highly trained on low frequency cues from head and torso to resolve front-back confusions.

Acknowledgements

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