Minimum Audible Angles Measured with Simulated Normally-Sized and Oversized Pinnas for Normal-Hearing and Hearing-Impaired Test Subjects

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Abstract The human pinna introduces spatial acoustic cues in terms of direction-dependent spectral patterns that shape the incoming sound. These cues are specifically useful for localization in the vertical dimension. Pinna cues exist at frequencies above approximately 5 kHz, a frequency range where people with hearing loss typically have their highest hearing thresholds. Since increased thresholds often are accompanied by reduced frequency resolution, there are good reasons to believe that many people with hearing loss are unable to discriminate these subtle spectral pinna-cue details, even if the relevant frequency region is amplified by hearing aids.

One potential solution to this problem is to provide hearing-aid users with artificially enhanced pinna cues—as if they were listening through oversized pinnas. In the present study, it was tested whether test subjects were better at discriminating spectral patterns similar to enlarged-pinna cues. The enlarged-pinna patterns were created by transposing (T) generic normal-sized pinna cues (N) one octave down, or by using the approach (W) suggested by Naylor and Weinrich (System and method for generating auditory spatial cues, United States Patent, 2011). The experiment was cast as a determination of simulated minimum audible angle (MAA) in the median saggital plane. 13 test subjects with sloping hearing loss and 11 normal-hearing test subjects participated. The normal-hearing test subjects showed similar discrimination performance with the T, W, and N-type simulated pinna cues, as expected. However, the results for the hearing-impaired test subjects showed only marginally lower MAAs with the W and T-cues compared to the N-cues, while the

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overall discrimination thresholds were much higher for the hearing-impaired compared to the normal-hearing test subjects.

1 Introduction

Spatial hearing relies on spatial acoustic cues. The binaural cues (interaural time and level differences, ITD and ILD) are reasonably well preserved with hearing aids, while monaural spectral cues can be substantially changed. The most striking example is that the spectral filtering imposed by the pinna is completely bypassed with behind-the-ear (BTE) hearing aids, because the microphones sit on top of the pinna. Pinna cues are useful for localisation out of the horizontal plane, and for resolving front-back confusions.

Previous attempts at providing hearing-aid users with natural pinna cues have only been partly successful (Jensen et al. 2013). A likely explanation is that the fine high-frequency spectral details (present from 5 kHz and upwards) of natural pinna cues are at least partly imperceptible by people with hearing impairment, due to reduced frequency selectivity.

Naylor and Weinrich (2011) described a hearing-aid configuration incorporating a method to create directional spectral cues with similar characteristics to pinna cues, but in a lower frequency region around 2–6 kHz, whereby they would be easier to perceive for hearing-impaired test subjects. The hypothesis was that hearing-aid users could learn to utilise these cues and thereby retrieve lost spatial hearing abilities. Hypothesised end-user benefits of such a method could be improved localisation out of the horizontal plane and in the front-back dimension, improved spatial unmasking, and improved spatial awareness in general.

A subsequent question is whether test subjects can learn to exploit a modified set of pinna cues. Hofman et al. (1998) and Van Wanrooij and Van Opstal (2005) reported about experiments where test subjects had their pinnae modified by concha moulds. Results show that while localisation performance was disrupted immediately after mould insertion, subjects regained their localisation ability over the course of weeks. Typically after 6 weeks of learning they had reached an asymptote close to their previous performance.

1.1 Main Research Question

In brief, the outcome measure of this study's experiment was the Minimum Audible Angle (MAA) in the vertical plane. This is the minimum angular change away from a given reference angle, which can be discriminated in a simulated set-up

with sound stimuli presented via headphones. The monaural spatial information is provided by different sets of pinna cues, either simulated normally-sized pinna cues or enhanced pinna cues either transposed one octave down or cues similar to what Naylor and Weinrich (2011) suggested. Thus, the MAA will be determined with normally-sized (N), transposed (T) or Weinrich (W) pinna cues.

The main research question was: Are the enhanced pinna cues (T or W) easier to discriminate than natural pinna cues (N) for hearing-impaired test subjects? Thus, is the MAA obtained with natural pinna cues (MAA_N) significantly larger than the MAA obtained with the two types of enhanced pinna cues (MAA_T, MAA_W)?

2 Method and Material

2.1 Pinna Cues

Three different cue-sets were used in the experiment, all artificially generated. The normally-sized pinna cues are designed to mimic key trends of recorded pinna cues found in literature (e.g., Shaw et al. 1997). Figure 1 illustrates the response of the normally-sized (N) pinna cue system to different incidence angles in the median saggital plane. Worth noticing is the low-frequency notch that moves upwards as
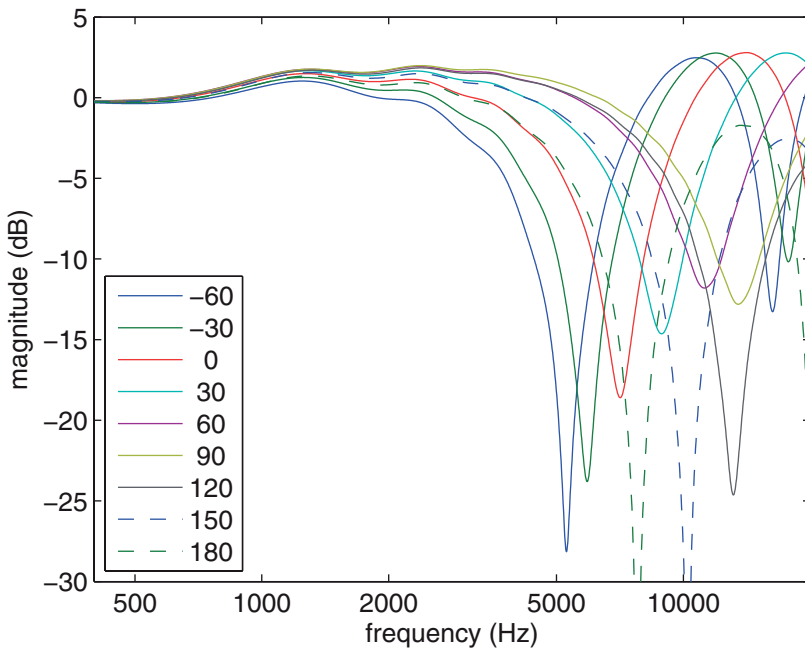

Fig. 1 Response pattern in the median saggital plane for the normal-cue system (N)
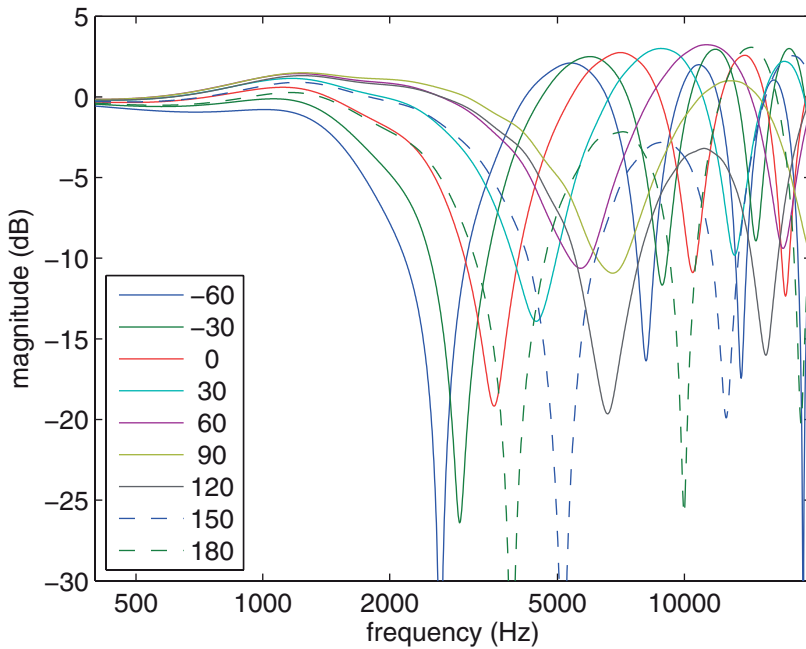
Fig. 2 Response pattern for the transposed-cues system (T)

the incidence angle moves away from 0° (0° = straight ahead, 90° = straight up). Figure 2 shows the transposed system (T), which was designed to shift the entire N-cue-structure one octave down. Figure 3 shows the (Naylor and Weinrich 2011) cue system (W).

2.2 Test Subjects

13 HI test subjects (33–79 years old, mean 64 years, SD 15 years) with no history of cognitive problems participated in the study. It was required that the uncomfortable level (UCL) was at least 15 dB higher than the hearing threshold (HTL), to ensure enough headroom for the hearing-loss compensation used to make stimuli audible.

11 test subjects with expected normal hearing were recruited for the NH group (21–52 years, mean 39 years, SD 11 years).

All test-subject audiograms were re-measured if older than 1 year, or if there was a suspicion that changes had occurred. The test subjects' individual hearing threshold levels for the test ear are plotted in Figs. 4 and 5.
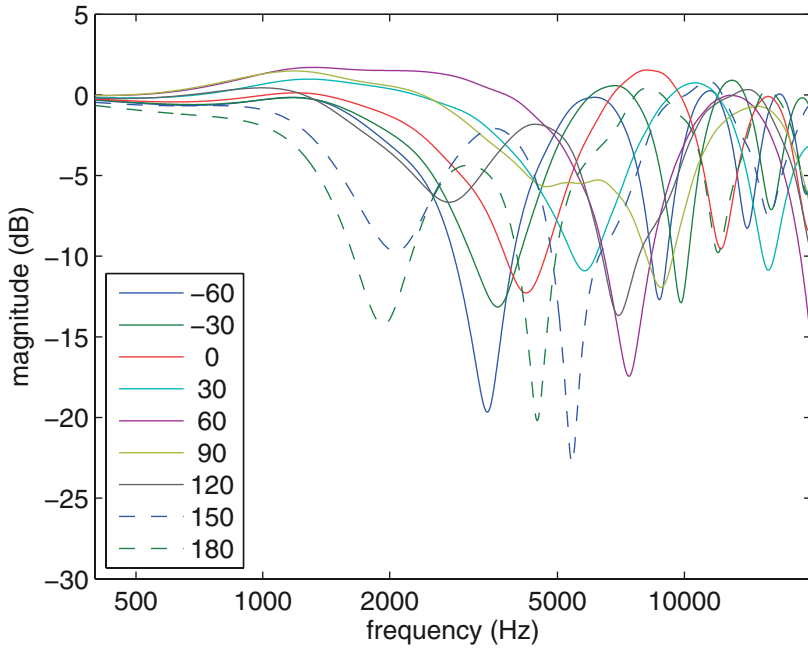
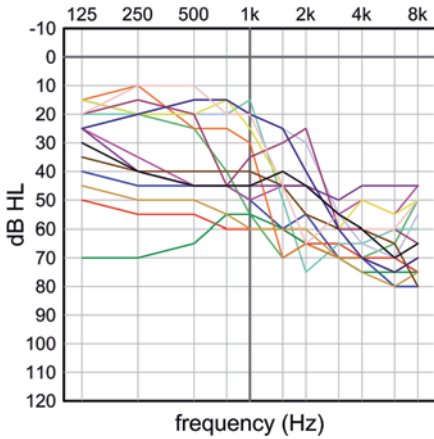**Fig. 3** Response pattern for the (Naylor and Weinrich 2011) cue system (W)

Fig. 4 Test-ear hearing thresholds of hearing impaired test subjects
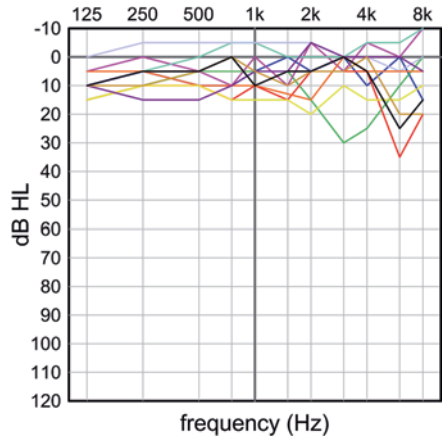

Fig. 5 Test-ear hearing thresholds of normal hearing test subjects

2.3   Psychoacoustic Experiment

An adaptive three-interval, three-alternative forced-choice (3-AFC) discrimination procedure, coupled with a one-up-two-down staircase rule tracking the 70.7 %-correct point on the underlying psychometric function, was used.

In each trial, three consecutive stimuli were presented. Two represented the reference incidence angle (0° or 120°) and one represented the variable angle (the 'target') determined by the adaptive procedure. The test subject's task was to determine the diverging stimulus by pressing one of three buttons on a touch screen, on which the target stimulus was randomly assigned to one of the buttons in each trial.

Following each response, the test subject was given visual feedback (about the correct answer) via the screen. In the first trial within a run, the initial incidence angle was easy to discriminate. Pilot testing suggested that appropriate values of the adaptive angle were 60° for the 0° reference and 180° for the 120° reference. The step-size was decreased along the run, with initial step size set to 8°. After each down-up reversal, the step size was halved, until a final step size of 2° was reached. After the final step size was reached, another eight reversals were completed.

The final MAA threshold estimate was calculated based on the median of the last three lower reversal points during a run. On average, this method provides a threshold value, which is lower than that produced by e.g. Levitt (1971) or Neher et al. (2011). However, data inspection indicated that both of these alternate methods could lead to misleading results if a test subject had been performing unreliably during parts of the run. Further, since this study investigates differences between conditions (cues) rather than the absolute MAA values, the consequently lower MAA was accepted.

2.4   Set-Up

The test took place in a single-walled, sound-attenuated test booth. The test software was run on a personal computer, which was connected to a 14" touch screen and a RME Hammerfall DSP Multiface II 24-bit soundcard running at 96 kHz sampling frequency. A Lake People phone-amp G103 was used to drive a pair of Sennheiser HDA 200 headphones.

2.5   Stimuli

All test stimuli were based on white noise samples generated by the test software and steeply band pass filtered to 0.4–16 kHz. The same frozen noise sample was used within each 3AFC triplet, while a new white noise sample was generated for

each new triplet. In each triplet, the simulated pinna cues were then added on the fly in Matlab.

Compensation for hearing loss was applied. In short, a level corresponding to 60 dB SPL(C) free-field was selected as the presentation level to be used with NH test subjects. For the HI test subjects, it was then ensured that in each one-third octave band the RMS level of the stimulus was at least 15 dB above hearing threshold before pinna-cue shaping. The required gain was added by designing an IIR filter in the test software to shape the stimulus. Note that the +15-dB gain strategy was terminated at 9 kHz. In higher frequency bands, the same gain as found for 9 kHz was applied, because of the lack of audiogram information. A similar approach was used towards the lowest frequencies.

2.6   Test Protocol

Both the NH and the HI test subjects completed nine test conditions: The MAA test in all combinations of two reference angles (0°/120°) and three cues (N/T/W), and further a front-back discrimination test with all three cues (these results are not reported in this paper).

The order of conditions was counterbalanced for the NH subjects, who completed all nine measurements within one visit. The testing of HI test subjects included two visits. The first visit included audiometry, if the existing audiogram was more than 1 year old, and the three MAA tests with 120° as reference angle. The second visit included the MAA tests with 0° as reference angle, the front-back tests, and a retest measurement (MAA at 0° with T cues). All visits included the same training conditions, T0 and N120. Within each visit, the order of test conditions was counterbalanced.

The blocking of the 120° measurements introduced a bias (visit effect) in the comparison of the 0° and 120° measurements, but this was preferred over a bias in the comparison between different types of cues, which was the essential comparison in this study.

3   Results

3.1   Data Inspection and Removal

Prior to analysis, the collected data were inspected. The subjective visual inspection of the adaptive MAA measurements pointed out 6 test runs, from which no reliable result could be extracted, as a performance plateau was never reached. These data points were removed.
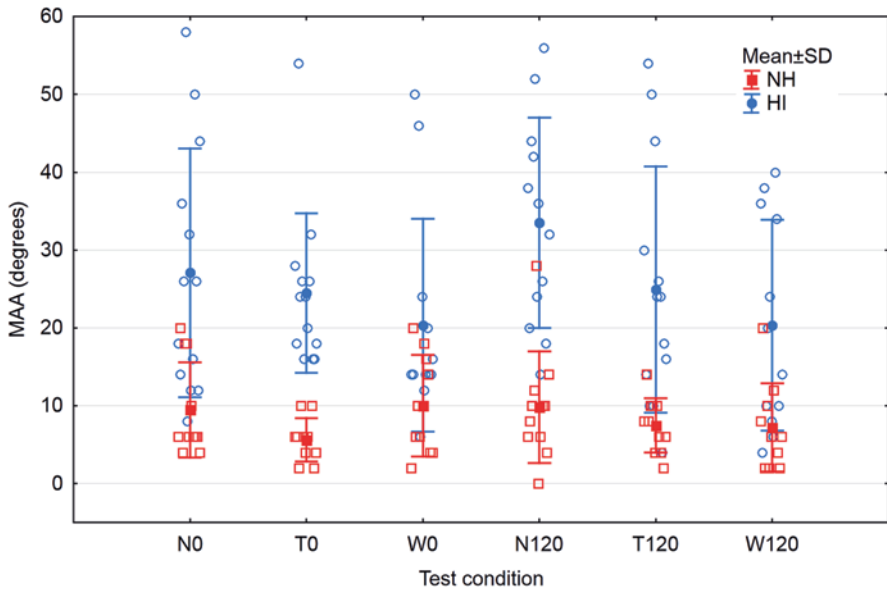
Fig. 6 Raw Minimum-Audible-Angle (MAA) data and mean±SD for the normal hearing (*NH*) and hearing impaired (*HI*) groups for each of the six test conditions

3.2 Raw Data and Descriptive Statistics

The MAA data for the NH and the HI groups are plotted in Fig. 6. The plot show raw and mean (±SD) data for each of the six MAA test conditions.

The main observations which can be made from Fig. 6 are:

- Substantially better (lower MAA) performance in the NH group.
- Large individual variation, especially in the HI group.
- Very small deviations between test conditions in the NH group.
- Some deviations between test conditions in the HI group, with better performance with W-cues than with N-cues (with T-cues in between), most pronounced for the 120° conditions.

A mixed-model ANOVA was used to analyze the NH MAA data. Besides a significant test-subject effect ($p=0.002$) (the random variable "test subject" was only included as a main effect), the various effects in the model came out as being non-significant, as already indicated by the rather similar mean values shown in Fig. 6. Thus, the NH-group performance did not depend on either cue type or reference angle.

Another mixed-model ANOVA was used to analyze the HI MAA data. As could be expected based on the large individual variance displayed in Fig. 6, a highly significant test-subject effect ($p<<0.001$) was observed. Furthermore, a significant effect of cue type was observed ($p=0.002$), while the effect of reference angle was non-significant. No interactions were significant.

Since the difference between normal and enhanced cues was the essence of the research question, the cue-type effect was further explored by conducting two planned comparisons, N vs. T and N vs. W (across the two reference angles). These analyses showed a significant difference between N and W cues (mean MAA difference of around 10°, $p=0.0005$) and a non-significant difference between N and T cues (mean MAA difference of around 5°, $p=0.06$).

3.3   Training Effects and Test-Retest Variability (Reliability)

Possible training effects, i.e. improved performance over time, were investigated by introducing 'test run number' as a variable. Neither the NH nor the HI subject analysis showed any significant within-session training effects.

The HI tests were conducted during two separate visits, thus enabling a possible between-visit training effect, but with two different sets of test conditions included at the two visits (MAA-120° conditions at first visit, MAA-0° and FB conditions at second visit), it was not possible to assess the between-visit effect. However, the fact that we found no reference-angle effects suggests that the between-visit effect, if present, was limited.

4   Discussion

4.1   Research Question

The hypothesis of the main research question was that the MAA is larger for normal cues than for enhanced cues in a group of HI test subjects. The results showed a significant MAA difference between N and W cues, but not between N and T cues. Thus, the hypothesis was confirmed for the W cues, but not confirmed for the T cues (even though the overall trend was the same in these data).

For the NH group, no differences in performance between cues were observed. This was as expected.

The NH data may be used as a reference in the discussion of the HI data. When the two data sets are compared (see Fig. 6), it is noteworthy that even though the use of enhanced cues improves the HI performance in the MAA measurements (from around 30° to around 20°), the mean performance with enhanced cues is still substantially poorer than NH mean performance, which is around 10° with all three types of cues. It may be questioned whether improving the MAA from 30° to 20° will result in any perceivable real-life benefit, but answering this question will obviously require further testing including training test subjects to exploit modified pinna cues.

4.2   Stimuli Level Differences—A Potential Discrimination Cue?

This study investigated whether the frequency-shaping differences caused by changes in pinna-cue filtering across different incidence angles were discriminable by test subjects. However, the subjects did not only have the frequency shaping to listen for, but consequently also a level cue. To quantify whether the level cue was large enough for the test subjects to take advantage of it, the rms-levels were calculated for the three different cue sets. Unfortunately, the specific hearing loss of a specific test subject, and the frequency range one includes in the analysis, very much affects the rms difference between different incidence angles, making it difficult to make conclusions. However, at large angular differences it was clearly observed that the level cue becomes prominent, whereas the level cue decreased with decreasing incidence angle. At average MAAs ($<35°$ for HI) level-cue magnitudes ($<$ approximately 1 dB) were found to be smaller than the level just-noticeable-differences for HI test subjects reported to be 1–2 dB (Moore 2003). This indicates that most subjects likely used the frequency-shaping cue rather than the level cue.

The test design could have addressed the potential level-cue issue by applying level roving. However, this would have made the test more difficult to perform, because subjects would have been forced to ignore these added level differences when performing the test. Thus, level roving was rejected to avoid the much more extensive training required, cf. Moore et al. (1989).

5   Conclusions

This study compared the ability to discriminate simulated normally-sized pinna cues with the ability to discriminate two different sets of simulated enhanced pinna cues, in a group of NH test subjects and in a group of HI test subjects, respectively. The results showed that the NH group discriminated equally well with all three sets of pinna cues, showing a mean MAA of around 10° across cue types and reference angle. In the HI group, use of W-cues improved the mean MAA from around 30° to around 20°. This improvement was significant and twice as large as the non-significant mean improvement (from around 25° to 20°) offered by the T-cues.

While the HI group showed an improved ability to discriminate enhanced pinna cues as compared to normal pinna cues, the improvements were not as large as expected, and performance was still substantially poorer than that observed in the NH group.

References

Hofman PM, Van Riswick JG, Van Opstal AJ (1998) Relearning sound localization with new ears. Nat Neurosci 1(5):417–421

Jensen NS, Neher T, Laugesen S, Johannesson RB, Kragelund L (2013) Laboratory and field study of the potential benefits of pinna cue-preserving hearing aids. Trends Amplif 17(3):171–188

Levitt H (1971) Transformed up-down methods in psychoacoustics. J Acoust Soc Am 49:467–477

Moore BC (2003). An introduction to the psychology of hearing, vol 5. Academic, San Diego

Moore BC, Oldfield SR, Dooley GJ (1989) Detection and discrimination of spectral peaks and notches at 1 and 8 kHz. J Acoust Soc Am 85:820–836

Naylor G, Weinrich SG (2011, May 3) System and method for generating auditory spatial cues. United States Patent

Neher T, Laugesen S, Jensen NS, Kragelund L (2011) Can basic auditory and cognitive measures predict hearing-impaired listeners' localization and spatial speech recognition abilities? J Acoust Soc Am 130(3):1542–1558

Shaw E, Anderson T, Gilkey R (1997) Binaural and spatial hearing in real and virtual environments. In: Gilkey RH, Anderson TR (eds) Acoustical features of human ear. Lawrence Erlbaum Associates, Mahwah, pp 25–47

Van Wanrooij MM, Van Opstal AJ (2005) Relearning sound localization with a new ear. J Neurosci 25(22):5413–5424