Loudness and lateralization of binaural broadband noise for subjects with asymmetric hearing loss

Lautheit und Lateralisierung von binaural breitbandigen Signalen bei Personen mit asymmetrischem Hörverlust

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Abstract

Loudness perception of binaural broadband sounds shows larger individual variations for hearing-impaired subjects after narrowband loudness compensation than for normal-hearing subjects. This is not taken into account in prescription rules for hearing aids that are based on the audiogram. The first goal of the present study was to compare the effects of symmetric and asymmetric hearing impairment on binaural broadband loudness perception. A narrowband loudness compensation rule based on audiometric pure tone thresholds was applied to two groups: eleven subjects with asymmetric and ten subjects with symmetric hearing loss. An additional goal was to compare spatial auditory impressions and lateralization perception for the two groups to the results for normal-hearing subjects. On average, the results of loudness scaling with binaural broadband noises indicated higher binaural broadband loudness summation for subjects with asymmetric than for subjects with symmetric hearing loss. With hearing threshold-based amplification, subjects with asymmetric hearing loss often perceived binaural broadband noise as lateralized towards the ear with the worse average hearing thresholds. Large individual differences were observed for asymmetrically hearing-impaired subjects with respect to both lateralization and loudness. Results of loudness scaling with monaural narrowband noises showed similar loudness functions for the left and the right ears, with the hearing-threshold-based amplification rule for subjects with symmetric hearing loss. However, for half of the asymmetrically hearing-impaired subjects, there were large and unexplained differences between the right and left ear loudness functions of more than 10 dB.

Keywords: hearing aid fitting, asymmetric hearing loss, binaural loudness, binaural fusion, loudness summation, lateralization

Zusammenfassung

Die Lautheitswahrnehmung von binaural breitbandigen Signalen weist bei Schwerhörenden nach schmalbandigem Lautheitsausgleich größere individuelle Schwankungen auf als bei Normalhörenden. Dies wird bei den Anpassformeln für Hörgeräte, die auf dem Audiogramm basieren, nicht berücksichtigt. Das erste Ziel der vorliegenden Studie war es, die Auswirkungen von symmetrischen und asymmetrischen Hörverlusten auf die binaural breitbandige Lautheitswahrnehmung zu vergleichen. Eine Methode für schmalbandigen Lautheitsausgleich, die auf den Hörschwellen des Audiogramms basiert, wurde bei zwei Gruppen angewendet: elf Personen mit asymmetrischer und zehn Personen mit symmetrischer Hörminderung. Ein weiteres Ziel war es, die räumlichen Höreindrücke und die Lateralisierung der beiden Gruppen mit den Ergebnissen von Normalhörenden zu vergleichen. Die Ergebnisse der Lautheitsskalierung mit binauralen breitbandigen Signalen zeigten bei Personen mit asymmetrischem Hörverlust im Durchschnitt eine höhere binaural breitbandige Lautheitssummation als bei Personen mit symmetrischem Hörverlust. Bei hörschwellenbasierter Verstärkung nahmen Probanden mit asymmetrischem Hörverlust binaurale breitbandige Signale häufig in Richtung des Ohrs mit der schlechteren mittleren Hörschwelle wahr. Große individuelle Unterschiede wurden bei asymmetrisch schwerhörenden Personen sowohl in Bezug auf die Lateralisierung als auch auf die Lautheit beobachtet. Bei Personen mit symmetrischem Hörverlust, die mit der hörschwellenbasierten Verstärkungsformel versorgt wurden, zeigten die Ergebnisse der Lautheitsskalierung mit monauralen schmalbandigen Signalen ähnliche Lautheitsfunktionen für das linke und rechte Ohr. Bei der Hälfte der asymmetrisch schwerhörenden Personen gab es jedoch große und nicht erklärbare Unterschiede zwischen den Lautheitsfunktionen des rechten und linken Ohrs von mehr als 10 dB.

Schlüsselwörter: Hörgeräteanpassung, asymmetrischer Hörverlust, binaurale Lautheit, binaurale Fusion, Lautheitssummation, Lateralisierung

Introduction

Hearing aids typically provide frequency- and level-dependent amplification. Prescription rules, such as NAL-NL2 [1], [2] or DSL [3], [4], [5], are based on hearing thresholds. NAL-NL2 uses a speech-intelligibility model to compute gains for maximizing speech intelligibility, while a loudness model limits the gains to achieve normal or less-than-normal loudness perception [1]. With increasing input level, gains are gradually reduced in all level-dependent threshold-based prescriptions for sensorineural hearing loss.

Despite this, hearing aids are often described as being too loud, which has to be corrected in fine tuning sessions or leads to dissatisfaction among users. In the EuroTrak 2018 survey in Germany only 66% of the respondents were satisfied with the comfort of loud sounds [6]. Rasetshwane et al. suggested that dissatisfaction might be due to the fact that hearing aid fitting methods are mainly based on measurements with pure tones presented monaurally [7]. In contrast, sounds encountered in daily life are predominantly broadband and received bilaterally. This fundamental discrepancy between common audiological practice and real auditory environments has important implications for loudness. First, the loudness of a sound increases if it is received bilaterally, relative to the case where the same sound is received at a single ear [8], [9], [10]. Second, loudness depends on the spectrum, so that for sounds with equal level well above thresholds, those with a wider bandwidth tend to be louder [11], [12]. Further, Edmonds and Culling showed that binaural loudness summation is different for correlated and uncorrelated narrowband noise [13]. However, Schlittenlacher et al. found no significant differences in reaction times between uncorrelated and diotic broadband noise [14]. Both binaural and spectral loudness summation are well-known phenomena describing the average perception of normal hearing and hearing-impaired subjects (for an overview, see [15]). However, in a hearing-impaired group, both types of summation are subject to individual differences that can be large and are arguably of retro-cochlear origin [16], but not considered in methods of fitting hearing aids to an individual with hearing loss.

Sounds from one source arriving at the two ears are typically perceived as a single auditory image. In this common case, there is no separable “left loudness” and “right loudness” [17], [18]. Instead, binaurally fused sounds evoke a single overall loudness that is based on combining the inputs from the two ears. Binaural fusion is also a prerequisite for perceiving sound within a continuous ”auditory space” [19]. Normal hearing (NH) subjects typically perceive a sound with no interaural level differences (ILD) and no interaural time differences (ITD) as originating from the sagittal plane if presented via loudspeakers [20] or from the center of their head if presented via headphones [21]. However, this is not always the case (see [22]), and for subjects with asymmetric hearing loss systematic deviations are common [23]. In this paper, asymmetric hearing loss is defined as having a PTA_4 (pure tone average at 0.5, 1, 2, and 4 kHz) difference between the left and right ears greater than, or equal to, 20 dB. For subjects with asymmetric hearing loss, regardless of the type of loss (conductive or sensorineural), neither stimuli that have the same intensity at the two ears nor stimuli that are perceived as equally loud at the two ears when presented sequentially result in centered auditory images. Instead, a stimulus level between equal loudness and equal intensity is required [23]. This means that subjects with an asymmetric hearing loss need a smaller ILD for perceiving a centered auditory image than is required for equal loudness in the case of sequential stimulation. It remains unclear, however, whether a fused percept can be assumed for subjects with asymmetric hearing loss when applying a threshold-based prescription rule to compensate for the hearing loss.

Loudness measurements are commonly used tools for initial fitting of hearing aids [24]. A method of quantifying loudness for fitting hearing aids is categorical loudness scaling [25], [26]. The monaural loudness of narrowband signals for hearing-impaired (HI) subjects with sensorineural hearing loss and symmetric hearing thresholds can be restored by means of frequency- and level-dependent gains (see, e.g., [15]). These gains correspond to the frequency-specific level difference between the HI listener and the average NH loudness function at equal loudness [27], [28], [29]. However, when subjects were presented with binaural broadband noise with these gains, loudness functions were found to show large individual variations. Some listeners showed similar loudness functions as observed for NH listeners, but for some listeners loudness was greater than normal [27], [28]. The individual differences in binaural broadband loudness perception could not be predicted from the audiogram or from narrowband loudness functions [27]. The origin of this effect is still unknown. These results indicate that fitting procedures based on the audiogram, or on monaural narrowband loudness functions, can result in hearing devices being too loud. Previous research studies on binaural or spectral loudness summation using the loudness matching procedure often showed no increased loudness summation in listeners with hearing loss (e.g., [30], [31], [32]). This directs to the assumption, that the individual variation of binaural and spectral loudness summation is an artefact of the categorical loudness scaling procedure especially after the general criticism of the procedure by [31]. Also Dillon concludes that "binaural loudness summation is equivalent to a smaller level change for hearing-impaired people" than for normal-hearing people as a fair summary of the data in the literature [33]. This summary holds for data on loudness summation up to 2012. Four conditions should be included in the measurement of loudness summation in the hearing impaired in order to demonstrate practice-oriented conclusions about individual differences: 1) broadband signals preferable with speech-like spectrum 2) binaural presentation 3) compensation of hearing loss 4) tested at loudness above medium. Often not all conditions were met for previous studies on loudness summation. The large individual variations including increased loudness summation for HI subjects with narrowband loudness compensation were reported starting in 2016 [28], [29], [34], [35]. Consequently, these data are not covered in [33]. Beurden et al. tested loudness summation with all four conditions and found large individual variation with loudness scaling and loudness matching [26]. Therefore, the individual variations are no artefact of the categorical loudness scaling procedure and might have a high impact on gain adjustments in hearing aids.

The two research questions for the current study are both based on a hearing threshold-based amplification: (1) Is the binaural broadband loudness summation for listeners with asymmetric hearing loss less than, equal to, or greater than for listeners with symmetric hearing loss? (2) How does the spatial auditory impression and lateral perception compare across subject groups with asymmetric, symmetric, and no hearing loss?

Methods

Subjects

Ten NH subjects (4 female, mean age: 39 years, standard deviation (SD): 8 years), ten symmetrically HI subjects (5 female, mean age: 74 years, SD: 6 years), and eleven asymmetrically HI subjects (5 female, mean age: 74 years, SD: 4 years) participated in the experiments. The average audiograms of the NH (panel A) and HI subjects with symmetrical hearing thresholds (panel B) are shown in Figure 1. The individual audiograms with air- and bone-conduction thresholds of the HI subjects with asymmetric hearing thresholds are shown in Figure 2.

Pure-tone, air-conduction (AC) audiometric thresholds were measured at octave frequencies (0.125, 0.25, 0.5, 1, 2, 4, and 8 kHz) as well as at several inter-octave frequencies (0.75, 1.5, 3, and 6 kHz). Bone conduction (BC) thresholds were measured at 0.5, 0.75, 1, 1.5, 2, 3, and 4 kHz. Thresholds were measured in 5-dB steps following the standardized procedure in DIN EN ISO 8253-1:2011-04 [36]. In particular when measuring BC thresholds, high sound pressure levels can result in a tactile perception instead of an auditory perception [37]. BC thresholds that lie above the vibrotactile thresholds are not reliable measured values and the supposed air-bone gap can lead to a misinterpretation of the type of hearing loss. Vibrotactile thresholds are frequency dependent with average values at 0.25 kHz of 37 dB HL, at 0.5 kHz of 58 dB HL and at 1 kHz of 76 dB HL [37]. True bone conduction thresholds cannot be determined above these levels. In cases of asymmetrical hearing loss, masking noise was presented to the better ear when measuring hearing thresholds in the worse ear, using the masking method of [31].

To meet the criterion for NH, the AC thresholds from 0.125 to 6 kHz were required to be less than or equal to 25 dB HL. The criterion was less strong compared to the typical criterion of 0.125 to 8 kHz with less than 20 dB HL to avoid excluding subjects with close-to-normal thresholds during the effortful data collection during the COVID-19 pandemic. Subjects were classified as having a hearing loss if their AC thresholds exceeded 25 dB HL for one or more of the frequencies between 0.125 and 6 kHz. The requirement for the symmetrically HI subjects was bilateral hearing loss with a difference in PTA_4 not exceeding 10 dB. Nine out of ten subjects with symmetrical hearing loss wore hearing aids bilaterally on a regular basis.

The inclusion criteria for the asymmetrically HI subjects were a difference in PTA_4 greater than or equal to 20 dB (following [38]) and bilateral hearing loss. Subjects with a PTA_4 difference between 10 to 20 dB were excluded from this study as they did not follow the inclusion criteria for symmetric nor for asymmetric hearing loss according to our definition. The mean absolute PTA_4 difference for the symmetric group was 4.9 dB (SD: 3.3 dB) while for the asymmetric group it was 29.9 dB (SD: 8.8 dB). The contribution of conductive hearing loss in the symmetric

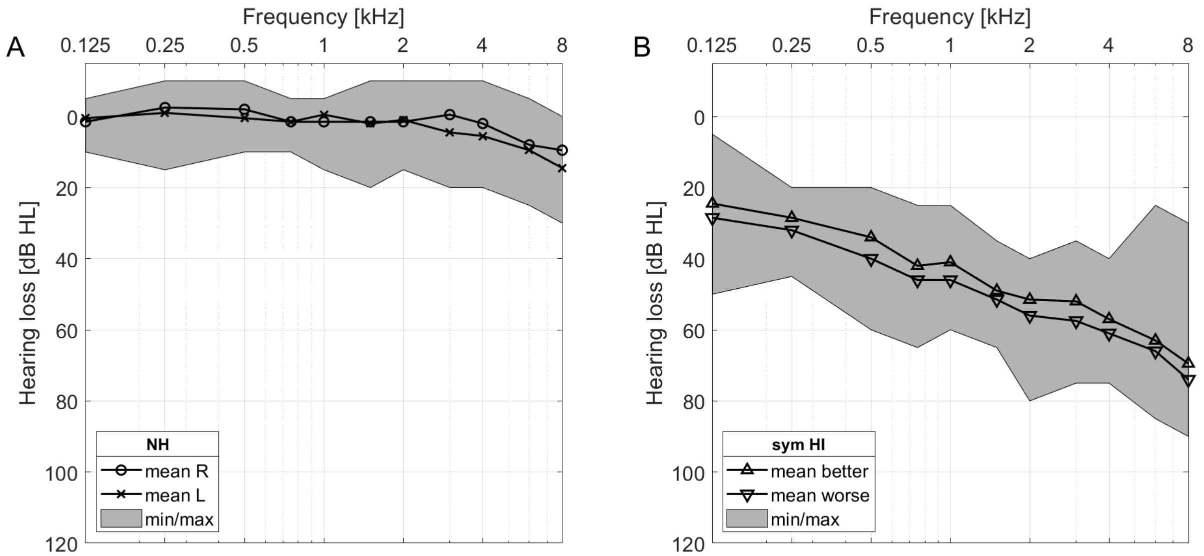

Figure 1: Average air conduction hearing thresholds for the right (R, symbol: o) and left (L, symbol: x) ears with the min/max range indicating minimal and maximal hearing thresholds for the NH listeners (panel A). Average air conduction hearing thresholds for the audiometrically better (symbol: △)/worse (symbol: ▽) ears with the min/max range for HI listeners with symmetric hearing thresholds (panel B)

and asymmetric HI listeners was limited for this study. The average air-bone gap at 0.5, 1, 2, and 4 kHz was 15 dB or less for all subjects.

There were several causes of asymmetric hearing loss. Subjects with Meniere's disease, sudden hearing loss, hearing loss due to explosions at work and hereditary causes participated in this study. However, some subjects did not know the reason for their asymmetric hearing loss. Also, the onset of hearing loss varied across subjects. Some subjects had suffered from asymmetric hearing loss since birth and some subjects only for a few years. Seven out of the eleven subjects with asymmetric hearing loss wore hearing aids bilaterally on a regular basis.

Subjects consented to participate in the study and were paid an hourly wage. All experimental procedures were approved by the Ethics Committee of the University of Oldenburg.

Equipment

For each subject, measurements were conducted in a single session of about 1.5 hours. Due to the COVID-19 pandemic, the measurement setup was designed such that the measurements could be carried out in the homes of the subjects. In such cases, the experiments were monitored remotely by the experimenter to avoid in-person contact. The calibrated measurement equipment was delivered in a suitcase to the subjects' homes. Two subjects of the asymmetrically HI group conducted the measurements in their homes. The remaining subjects conducted the measurements with the suitcase in a sound-insulated booth at Hörzentrum Oldenburg. The symmetrically HI group performed the same measurements with permanently installed equipment in a sound-insulated booth as lower COVID restrictions allowed for returning to in-house measurements in the data collection phase. The equipment in the sound-insulated booth for the symmetrically HI group was the same as the equipment in the suitcase for the NH and asymmetrically HI groups. For all groups, pure-tone audiograms with AC and BC were measured with a Madsen Astera 2 audiometer using Sennheiser HDA 200 circumaural headphones and B71 bone-vibrator. For the two subjects in the asymmetrically HI group who conducted the experiments remotely, the most recent measured audiogram from the Hörzentrum Oldenburg database was used. Sennheiser HDA 200 headphones were also used for all subsequent measurements using the AFC-framework for psychoacoustic experiments [39] running in MATLAB. Signals were presented using an RME Fireface UCX audio interface with 44.1 kHz sample rate and 32-bit resolution. For calibration of the measurement setup, a Brüel & Kjaer artificial ear type 4153 with an integrated ½" pressure field microphone type 4192, a microphone preamplifier type 2669 and a measurement amplifier type 2610 were used. The measurement amplifier was calibrated with an acoustic calibrator type 4231. For signal calibration, the headphones were free-field equalized according to DIN EN ISO 389-8:2004-11 [40]. All levels are expressed as the equivalent free-field levels in dB SPL (FF).

Stimuli

If not stated otherwise, stationary broadband "IFnoise" (International Female noise; [41]) derived from the long-term average of the female speech spectrum was used [42]. All stimuli were gated with 50-ms Hann rise and fall ramps and had a duration of 1 s. For all experiments, the unprocessed signals were diotic and NH listeners rated diotic signals. The signals for HI subjects were not diotic as the applied frequency-dependent gains varied between

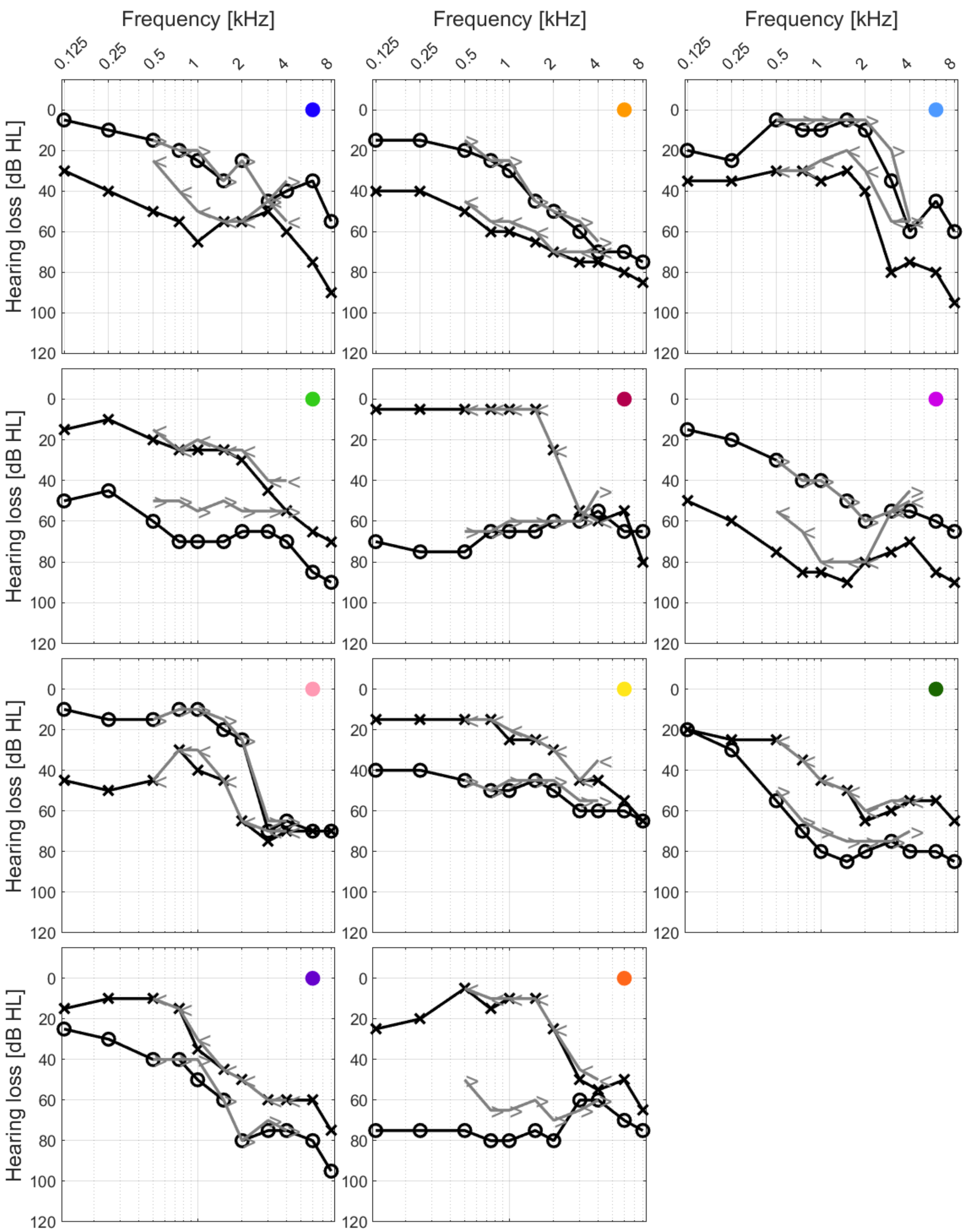

Figure 2: Individual air- and bone-conduction hearing thresholds for eleven subjects with asymmetric hearing thresholds. Black graphs represent air-conduction, gray graphs bone-conduction hearing thresholds. Standardized audiometry symbols indicate the measured ear (o, >=right ear; x, <=left ear). The colored dot indicates the color used to identify the individual subject results in group plots throughout the manuscript.

the ears as the hearing thresholds for the left and the right ear were not identical.

Procedure

Hearing loss compensation

Hearing loss was compensated for in a frequency- and level-dependent manner. Normal hearing reference function at the frequencies 0.25, 0.5, 1, 2, 4, and 6 kHz from [43] were used. The values are given in Attachment 1, Table 1. To perform such compensation, normally full categorical loudness scaling at six frequencies for each ear is conducted [27], [28], [29], [35]. While this procedure captures the individual monaural loudness of narrowband signals, it takes about 30 minutes and is therefore too time consuming for audiologic practice.
The validation of the gain estimation derived from the hearing thresholds was done in [43] and led to comparable gains as the procedure where the narrowband loudness functions were measured individually [27]. Loudness functions for 26 NH listeners and 223 HI listeners were used to derive average loudness functions depending on the test frequency and the hearing threshold following the procedure described in [43]. The parameters describing the loudness functions can be found in Attachment 1, Table 2.
To apply the individual hearing-loss compensation, the test signals were transformed to the frequency domain using the discrete Fourier transform. Six non-overlapping channels were defined at the six center frequencies 0.25, 0.5, 1, 2, 4, and 6 kHz. Edge frequencies were defined as the geometric mean values of the adjacent center frequencies. The channel level in dB SPL of the test signal was calculated and the NH loudness in CU was derived using the NH reference loudness function. For the transformation between dB HL and dB SPL the values for the hearing threshold according to ISO 226:2023 [44] were used. The level difference at equal loudness between the NH reference function and the individual HI loudness function was used as the gain at this center frequency. Linear interpolation on a logarithmic frequency scale and the gain scale in dB between the center frequencies was used to smooth the applied gain values. A detailed description of gain calculation and gain application to the signals can be found in [27].
For HI subjects with symmetric hearing loss, it has been shown that estimating the narrowband loudness functions from the hearing threshold can save a significant amount of time. The median of the gain deviation with the hearing threshold-based narrowband loudness compensation of Suck et al. compared to the conventional full loudness-scaling-based compensation was about 0 dB with an interquartile range of about 7.8 dB (cf. Figure 2b in [43]). The gain deviations of the threshold-based estimation of narrowband loudness function were similar to the interquartile range of the test-retest results with individually measured narrowband loudness functions of 7.5 dB [43]. The hearing threshold-based narrowband loudness compensation remained unevaluated for asymmetrically HI subjects. This study was designed to assess whether after estimated narrowband loudness compensation, the two ears of asymmetrically HI subjects contributed equally to the perception of binaural broadband noise. An unbalanced contribution could lead to reduced binaural loudness summation, to reduced binaural fusion, or to binaural stimuli being perceived as lateralized. For the sake of brevity throughout the manuscript, the applied hearing-threshold-based narrowband loudness compensation will be referred to as "hearing-loss compensation" (HLC). No compensation was applied for NH subjects, even if their thresholds were not equal to 0 dB HL.

Binaural broadband loudness scaling

Following HLC, adaptive categorical loudness scaling (similar to ACALOS, [25]) was performed to assess the individual loudness of binaural broadband noise. The task of the subjects was to describe the perceived loudness on a scale with eleven categories, from "not heard" to "extremely loud" (response scale in Table A.1 in [26]). Each category was assigned a numerical value in CU (categorical unit of loudness) between 0 and 50. The stimuli were presented at different levels in a pseudo-randomized order. A complete run consisted of 22–25 presentations.
Details and differences between fitting methods for loudness functions from [45] of responses 22–25 are given in Attachment 1, section A2. In this study, the BTUX fitting method was used to estimate the individual loudness functions [45]. An average loudness function was calculated for each group. To calculate the average loudness function, the level for all eleven loudness categories between 0 CU und 50 CU were calculated from the individual loudness function. Median levels for each loudness category were calculated for all eleven loudness categories. The BX fitting method (see Attachment 1, section A2, [45]) was used to fit the average loudness function to the medians of each group.
For safety, the maximal presentation level (input level + gain) was limited to 100 dB SPL. Prior to the main measurements, the subjects participated in a short training session using binaurally presented one-third-octave wide, low-noise noise [46], [47] centered at 1 kHz created using Method 1 with one iteration from [46].

Binaural fusion

To assess the in-head localization of binaural broadband noise with the above-mentioned hearing-loss compensation, an experiment assessing binaural fusion and lateralization was conducted. The subjects had to report the number of perceived auditory images and their in-head positions by selecting one of nine response options. The options are 1) one auditory image slightly on the left; 2) one auditory image in the center; 3) one auditory image slightly on the right; 4) one auditory image on the far left; 5) one auditory image on the far right, 6) two auditory images with equally strong left and right perception, 7) three auditory images left, center, right; 8) two auditory image with left strong and right weak perception; 9) two auditory images with left weak and right strong perception. The stimuli were presented at levels corresponding to 15, 25, and 35 CU ("soft", "medium", "loud") as predicted by the individual binaural broadband loudness functions (see Binaural broadband loudness scaling). Each stimulus was presented five times for each loudness category, resulting in 15 ratings per subject. Stimuli were presented in a randomized order. In cases where levels would have exceeded 100 dB SPL for the 35 CU condition, only the levels corresponding to 15 and 25 CU were presented. Subjects were not allowed to repeat the stimuli. To familiarize the subjects with the task and the stimuli, an example stimulus from each loudness category was presented prior to starting the main experiment.

Centralization

In order to find the levels required to evoke centralized auditory images, we altered the level in one ear, with a fixed-level reference in the other ear. The stimuli were the same binaural broadband noise as used in the categorical loudness scaling, binaural fusion, and lateralization tasks. For all HI subjects, the level at the audiometrically better ear was held constant, whereas for the NH subjects, the level at the right ear was held constant. Levels for 15, 25, and 35 CU were used for the "constant-level ear", corresponding to the individual's binaural broadband loudness function at 15, 25 and 35 CU ("soft", "medium", "loud") with HLC. The centralization procedure was implemented as a two-interval, two-alternative, forced-choice procedure following a one-up, one-down adaptive rule, converging on the 50% point of the psychometric function [48]. For each condition, one run was performed with a starting level twice the initial step size specified below the reference, and another run was performed starting at twice the initial step size above the reference. For the 15 CU condition, the starting level was one initial step size below that of the reference and for the 35 CU condition, the starting level was one initial step size above that of the reference. In total, six runs per subject were conducted and presented in an interleaved manner. Step sizes decreased during the measurement, and the track converged to the CU value that produced a centralized auditory image. The initial step size corresponded to a level change of 5 CU. The step was decreased to 2.5 CU after the first upper reversal. The smallest step size corresponding to 1.5 CU was used after the third upper reversal. For the NH group, a difference of 1.5 CU was obtained by a level change of about 2.8 dB at 25 CU. For the symmetric and asymmetric HI listeners, the level changes were less due to the reduced dynamic range. For the average hearing thresholds of the symmetric HI listeners, a difference of 1.5 CU was obtained by a level change of about 1.7 dB.
The measurement was completed after five reversals with the smallest step size. The final value for each track was calculated as the mean of the last four reversals. Afterwards, the mean for each condition with starting level above and below that of the reference was calculated. For training purposes, the 25 CU condition with starting level below that of the reference was completed by each subject before the main experiment started. The maximum presentation level was either 100 dB SPL or the level corresponding to 45 CU of the binaural broadband loudness function. Otherwise, the corresponding condition was not presented, or it was stopped if the maximum value was reached twice during the track. Tracks that would have started above 100 dB SPL were skipped. In cases where the track was terminated due to reaching the maximum value twice, the maximally reached loudness (mostly 45 CU) was used as the final track value. The experiment was implemented with an adapted version of the MATLAB code used by [29].

Results

Binaural broadband loudness scaling

The first research question was whether the loudness of binaural broadband noise differs between listeners without hearing loss, symmetric hearing loss and asymmetric hearing loss after HLC and method of [43]. Loudness functions that were derived from the results of the binaural broadband categorical loudness scaling were analyzed. Figure 3 shows the average loudness functions and interquartile ranges at 15, 25 and 35 CU for asymmetrically HI subjects (light gray), symmetrically HI subjects (dark gray), and NH subjects (black). The level on the x-axis corresponds to the input signal level, i.e., before HLC was applied.
For statistical comparison between groups, input levels corresponding to 15, 25, and 35 CU ("soft", "medium", "loud") of the individual binaural broadband loudness functions were used. For all statistical tests, the significance level was set at 5%.
Levene's tests were performed to assess the homogeneity of variances across groups, and significant differences between the three groups were found at each CU value. Since homogeneity could not be assumed, no multifactorial ANOVA could be conducted. Instead, a Welch-ANOVA was conducted for each loudness category separately. If a significant effect was reported by the Welch-ANOVA, Bonferroni-corrected post hoc two-sample t-tests for unequal variances were performed to determine which pairs of groups differed.
The results of the Welch-ANOVA were highly significant for each loudness category (15 CU: $F(2,17.6)=13.32$, $p<0.001$, 25 CU: $F(2,17.4)=16.24$, $p<0.001$, 35 CU: $F(2,14.6)=14.63$, $p<0.001$). Bonferroni-corrected post hoc tests (p-values from the pairwise comparisons were multiplied by three) indicated that the loudness ratings of each loudness category were reached at significantly different input levels for all groups ($p<0.05$) except that the two HI groups at 15 CU ($p=0.24$) and 25 CU ($p=0.067$)

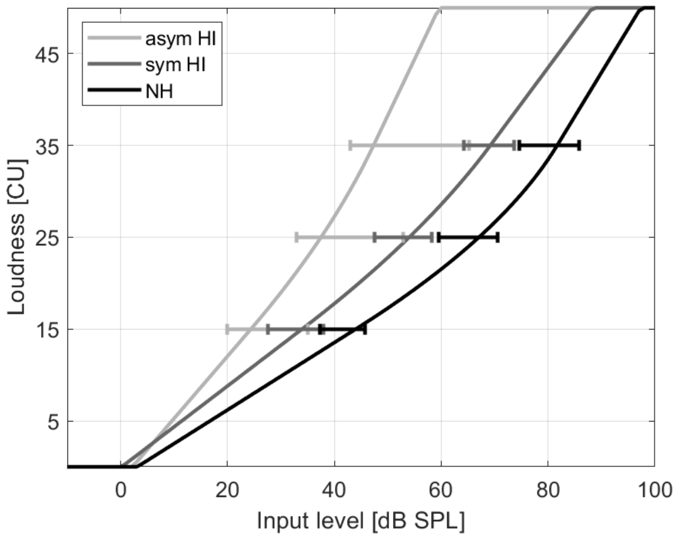

Figure 3: Average binaural loudness functions with interquartile ranges at 15, 25 and 35 CU measured with broadband IFnoise for subjects with normal hearing thresholds (black) and with hearing-loss compensation for subjects with symmetric hearing thresholds (dark gray), and asymmetric hearing thresholds (light gray)

were not significantly different. Particularly at higher loudness, the differences between asymmetrically HI subjects and the other groups were large. For instance, the difference at 35 CU between asymmetrically HI subjects and NH subjects was 27 dB, and the difference between asymmetrically HI subjects and symmetrically HI subjects was 16 dB.

Near threshold (2.5 CU), the average loudness functions showed similar levels, between 5 and 10 dB SPL, effectively validating the audiometrically obtained thresholds.

Binaural fusion

The binaural-fusion experiment was conducted to investigate lateralization and the number of perceived auditory images for hearing-loss-compensated binaural broadband noise. The signals were identical to those used for categorical loudness scaling and were presented at levels corresponding to 15, 25, and 35 CU, based on the binaural broadband loudness function.

Figure 4 shows the relative frequencies of the response categories used for the description of the spatial percepts. Subgroups were used to distinguish between perceptions of (1) single binaurally fused auditory images perceived as (nearly) central, (2) lateralized towards the worse ear (left ear for NH subjects), (3) lateralized towards the better ear (right ear in NH subjects), (4) multiple auditory images (not binaurally fused) perceived as balanced, or (5) multiple unbalanced percepts. For NH and symmetrically HI subjects each column (e.g., 15 CU) contains responses from 50 trials (ten subjects with five measurement repetitions each). For asymmetrically HI subjects, one column contains responses from 55 trials.

As expected, for NH subjects, most stimuli were perceived as (nearly) central. Only a few stimuli were perceived as lateralized towards the right ear or as two auditory images. The highest percentages in all three groups for a nearly central perception was at medium loudness. For soft (15 CU) and loud (35 CU), the numbers were lower than for medium loud (25 CU). The reason for this pattern in all three groups were unclear. In both hearing-impaired groups just over 50% of the responses were given to the “(nearly) central” response categories and 8–16% of the stimuli were perceived as not binaurally fused. The remaining 26–38% of the stimuli were perceived as a lateralized, binaurally fused auditory images.

In the symmetrically HI group (mean absolute PTA_4 difference 4.9 dB), the lateralization was more often towards the better ear (21%) than to the worse ear (13%) when averaged across all three loudness categories. The difference primarily originates from the loud condition. In contrast, in the asymmetrically HI group about 28% of the stimuli were perceived as lateralized towards the worse ear and only 3% to the better ear.

In each group, several subjects gave responses in different response categories across repetitions of the same stimulus. This means that the large variability is not only due to individual differences, but also to the uncertainty of the subjects.

Centralization

The main question here was whether the binaural broadband noise used in the categorical loudness scaling resulted in centered auditory images. Figure 5A shows the input-level differences that, given a fixed-level reference in the audiometrically better ear, were needed in the audiometrically worse ear of the HI subjects (left ear for the NH subjects) to evoke a centered percept. In the case of identical input levels for the two ears (input level difference=0 dB), the signal levels were identical to those used in the categorical loudness scaling and binaural-fusion experiments.

While all NH subjects and most HI subjects with symmetric loss had a central percept for interaurally similar input levels, large level differences were required for many of

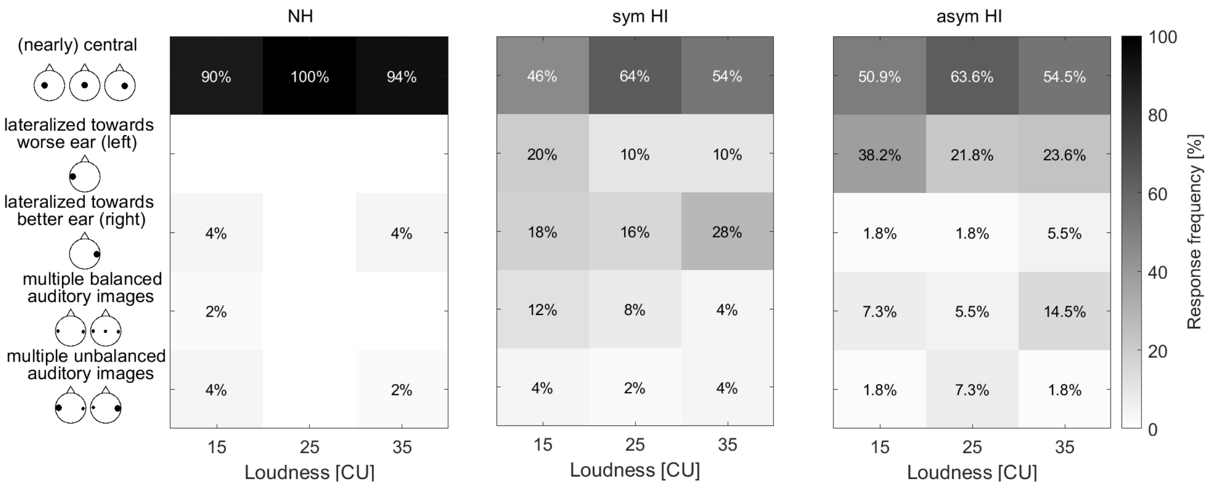

Figure 4: Relative frequencies of the different response categories for the three subject groups. Left: NH subjects, middle: symmetrically HI subjects, right: asymmetrically HI subjects. For both HI subject groups, a distinction was made between the better ear and the worse ear; for NH subjects, a distinction was made between the right ear and the left ear.

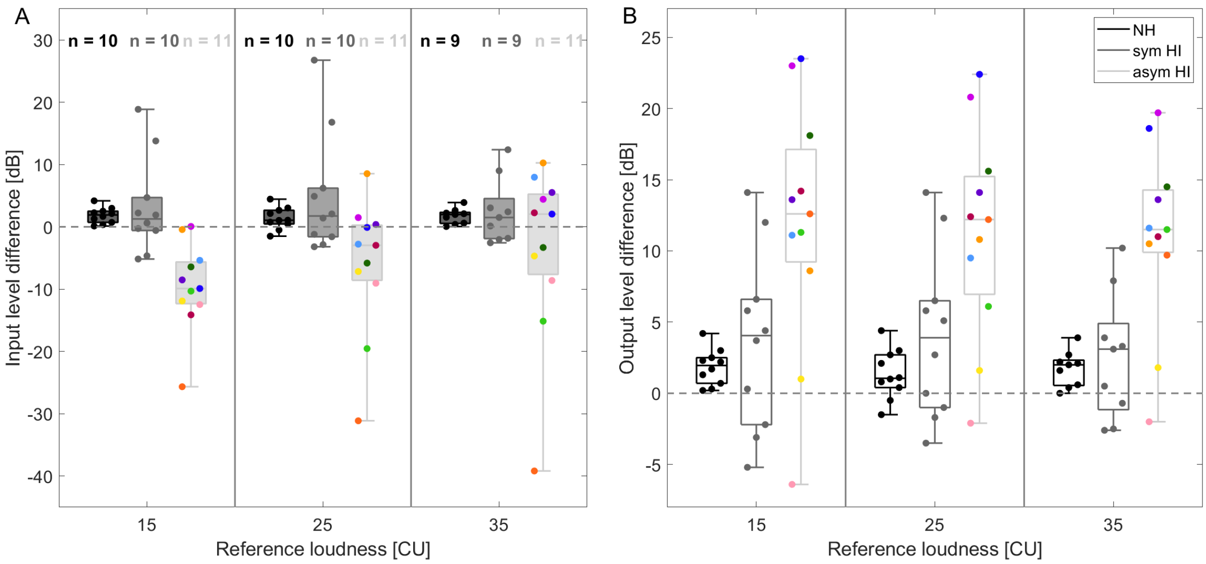

Figure 5: Level differences required for a central percept of broadband noise when stimulating both ears simultaneously. A: Input-level differences. B: Output-level differences, also referred to as ILDs. For both panels, the black boxes represent NH subjects, dark gray boxes represent HI subjects with symmetric hearing thresholds, and light gray boxes represent HI subjects with asymmetric hearing thresholds. The colored symbols represent individual data. Three fixed levels corresponding to 15, 25, and 35 CU were presented to the audiometrically better ear. Positive values indicate that to obtain a central percept, a higher level was required at the worse ear.

the asymmetric HI subjects. To obtain a centralized percept in the “soft” 15 CU condition, the input level at the audiometrically worse ear had to be reduced by more than 5 dB for nine of eleven asymmetrically impaired subjects (81%). For the “loud” 35 CU condition, this was the case for three of the subjects (27%).

To compare the groups more quantitatively, statistical tests were conducted. Homogeneity of variances was assessed using Levene’s test. Since equal variances between the groups could not be assumed (15 CU: $p=0.024$, 25 CU: $p=0.022$, 35 CU: $p=0.0020$), we conducted a separate Welch-ANOVA for each loudness category. Significant differences between groups at 15 CU were revealed ($F(2,13.4)=13.3$, $p<0.001$) but not at 25 CU ($F(2,13.4)=3.1$, $p=0.076$) and 35 CU ($F(2,12.2)=0.29$, $p=0.75$). Conservative Bonferroni-corrected post hoc analysis (p-values were multiplied by 3) for 15 CU with t-tests for unequal variances showed a significant difference between the NH group and the asymmetrically HI group ($p<0.001$) and between the two HI groups ($p=0.0028$). The difference between NH subjects and symmetrically HI subjects was not significant ($p=0.60$, uncorrected).

Further t-tests were conducted to analyze whether the group mean values differed from zero. A significant difference was found at 15 CU ($p=0.0012$) for subjects with asymmetric hearing loss but not at 25 and 35 CU with $p=0.089$ and $p=0.43$, respectively. On average, the input level to the audiometrically worse ear had to be reduced by 9.5 dB to produce a central percept. These results are consistent with the results from the binaural-fusion experiment. At equal input levels, asymmetrically HI subjects reported strong lateralization towards the audiometrically worse ear in approximately 30% of the presentations. Significant differences in the input level to the reference ear were also found for NH subjects at 15, 25 and 35 CU with p=0.0013, p=0.036 and p=0.0029, respectively. For all CU values, the level had to be higher at the left ear than at the right ear to achieve a central percept (15 CU: ΔL=1.3 dB, 25 CU: ΔL=1.8, 35 CU: ΔL=1.5 dB). In the case of symmetrically HI subjects, none of the group mean values for the three CU values differed significantly from zero (all p-values >0.05).

As indicated by the number of subjects at the top of Figure 5A, for each of the NH and symmetrically HI groups, one subject was unable to complete the centralization procedure at 35 CU because this condition would have required sound pressure levels above 100 dB SPL. Thus, fewer data points were acquired at 35 CU than at the two lower CU. In addition, some of the measurements for all loudness conditions and both methods of level control (starting above and below the reference) were stopped because the maximum or minimum values were reached twice. This occurred in 10% of the cases of the two HI groups. The maxima/minima were taken as final track values, even though there was probably no central percept.

While Figure 5A and the description of the results so far were based on the input levels that resulted in a centralized auditory image, Figure 5B shows the corresponding output level differences. Output levels were obtained by applying the individual gain depending on the input levels at 15, 25 and 35 CU. The resulting ILDs (interaural level differences including the gain used for hearing-loss compensation) that resulted in centralized percepts are plotted in Figure 5B. A positive median value indicates that to evoke a central auditory image, a higher level was needed at the audiometrically worse ear of the HI subjects.

Interestingly, the output level difference resulting in a centralized auditory image is visually the same for soft, medium, and loud sounds, even on an individual level. On average, an ILD of 11 dB was required for centralization in HI listeners with asymmetric hearing loss. Despite a large range of audiometric asymmetries (difference in PTA_4 between left and right ear: 21 to 50 dB), the interquartile range was similarly small as for symmetrically HI subjects and ranged from about 10 to 15 dB at 25 and 35 CU. That said, two asymmetrically HI subjects (pink and yellow) with PTA_4 differences of 23 and 26 dB respectively, deviate strongly from the median and required an ILD close to zero or even a negative ILD.

For NH subjects, the values between Figure 5A and Figure 5B are identical as no gain was applied.

Monaural narrowband loudness scaling

A possible reason for the large variability in the results for the HI groups in Figure 5A could be that the HLC was less accurate than expected from the results in [43] and the standard deviations associated with measurements based on the ACALOS procedure [25]. To test the accuracy of the threshold-based compensation method, an additional ACALOS was conducted using monaural narrowband noise stimuli with the HLC.

Uniformly exciting noise with a bandwidth of one Bark (UEN1, [49]) was used. The center frequency of the UEN1 was 1.37 kHz (10.5 Bark), where the width of 1 Bark equals 210 Hz. As before, stimuli were gated with 50-ms Hann rise and fall ramps and had a duration of 1 s. Input levels for the right and the left ears (Figure 6A) and the resulting input-level differences (Figure 6B) were assessed for equal monaural loudness corresponding to 15, 25, and 35 CU.

If HLC had worked perfectly, we would have obtained identical results for all subjects across groups, as the gains were calculated to match the average NH loudness function. Based on [43] we expected similar results between groups and an average deviation of about 4 dB for both HI groups.

Both NH and symmetrically HI subjects met our expectation of showing similar input levels at 15, 25, and 35 CU, with interquartile ranges <10 dB (Figure 6A) for the latter group. For the asymmetric HI subjects, the interquartile ranges were larger than expected, ranging from 7 to 16 dB.

For all groups, the median interaural input level differences were close to zero (Figure 6B). For most subjects in the NH group and the symmetrically HI group, the level differences were small, indicated by interquartile ranges of approximately 5 dB. The smaller interquartile ranges in Figure 6B compared to Figure 6A reveal that if subjects reported an above- or below-group average loudness for one ear, they had a similar trend for their other ear. Deviations were subject specific, rather than ear specific for NH and symmetrically HI subjects.

For the asymmetrically HI group, interquartile ranges did not decrease (comparing Figure 6B to Figure 6A) as for the other two groups. Instead, interquartile ranges became even larger and spanned a range up to 25 dB. Groupwise F-test with Bonferroni corrections were performed to assess the significance of differences in variances of interaural input level differences between groups (Figure 6B). No significant differences were found between NH listeners and symmetric HI listeners with p>0.05. The HI listeners with asymmetric hearing loss showed significant differences to the NH group for all loudness categories with p=0.002 for 15 CU and p<0.001 for 25 and 35 CU. The differences between symmetric and asymmetric HI listeners were significant for 25 and 35 CU (both p=0.020), but not for 15 CU (p=0.11).

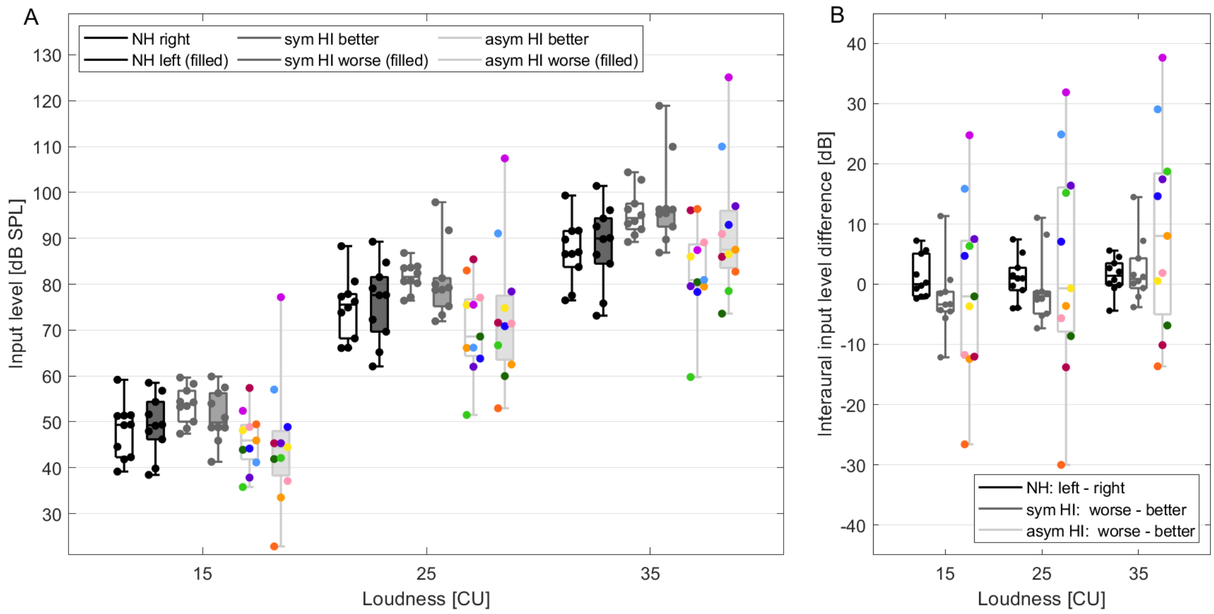

Figure 6: A: Input levels resulting in loudnesses of 15, 25, and 35 CU for a hearing-loss compensated narrowband signal (UEN1) presented monaurally. Colors and symbols correspond to the same subjects as in Figure 4. Data points in filled boxes represent results from NH subjects' left ears and HI subjects' audiometrically worse ears. White boxes represent results from right ears (NH) and audiometrically better ears (HI subjects). B: Interaural input level differences between the two ears are shown in panel B. The black boxplots represent the differences between left and right ears for NH subjects. The dark gray and light gray boxplots represent the difference between audiometrically worse and better ears for the groups with symmetric hearing thresholds and with asymmetric hearing thresholds, respectively.

To summarize, the results of the narrowband categorical loudness scaling confirm the accuracy of hearing-threshold-based narrowband loudness compensation for subjects with symmetric hearing loss. On average, the interaural level differences of the groups did not differ significantly. However, the compensation procedure was not a suitable method for subjects with asymmetric hearing loss as large differences between both ears persist. This means that the loudness functions of individual subjects with asymmetric hearing loss should not be expected to be similar to those of NH subjects after threshold-based compensation – not even in case of monaurally presented narrowband stimuli.

Discussion

Binaural broadband loudness scaling, binaural fusion, centralization and monaural narrowband loudness scaling were measured for subjects with asymmetric and symmetric hearing loss as well as NH subjects. Data were recorded and reported following HLC [43]. To our knowledge, the present work was the first to apply this HLC method to asymmetrically HI subjects. Since approximately 8% of HI people are affected by asymmetric hearing loss (PTA_4 difference greater than 20 dB, [38]), the hearing-aid fitting requirements specific to this group of subjects should not be neglected.

One main finding was that asymmetrically HI subjects, following hearing threshold-based amplification, reported a loudness of 35 CU ("loud") for an average binaural broadband signal at an input level of 53 dB SPL (Figure 3). This is 27 dB lower than the 80 dB SPL associated with 35 CU with the same binaural broadband noise for NH subjects and 16 dB lower than the 69 dB SPL for symmetrically HI subjects.

This large 27 dB deviation from NH listeners would be important for hearing-aid fitting and for the listening experience of many asymmetrically HI hearing aid users. It is arguably a compound effect of many components, but especially the following three: (1) deviation of the individual narrowband monaural loudness from its hearing threshold-based estimate, (2) differences in spectral loudness summation, and (3) differences in binaural loudness summation.

To quantify the first component in isolation, the results for the UEN1 with narrowband loudness compensation of the asymmetrically HI group can be compared to the NH listeners (Figure 6A). The spread of the data is larger for the asymmetrical HI group than for the NH group. The median value of the asymmetrical HI group is lower than the median of the NH group indicating that the narrowband loudness compensation did apply on average slightly too high gains for narrowband signals in the asymmetric group. We could speculate about the changes of the results if the individual narrowband loudness function would have been measured using categorical loudness scaling. We expect median values closer to NH values in Figure 6A. The individual variations are expected to be in the range of the symmetric HI group. Overall, it would have led to lower gains that would have been applied for hearing-loss compensation compared to the HLC procedure used here. The individual measurement of narrowband loudness function does not explain, why an over-

compensation for binaural broadband signals was observed in the asymmetrical HI group (Figure 3).
Therefore, the deviation of the individual narrowband loudness function from the threshold-based estimate might have only limited impact of the 27 dB deviation at the tested frequency (UEN1 centered around 1.37 kHz). While not knowing the effect size at other frequencies, the bulk of the 27 dB deviation is expected to be associated with the increased spectral and/or binaural loudness summation.
Increased average loudness summation for broadband signals after HLC for subjects with symmetrical hearing thresholds has been reported [27], [28]. Verhey et al. found that the amount of spectral loudness summation is reduced or absent in hearing-impaired subjects as compared to listeners with normal hearing [50]. They used bandpass-filtered white noise as test signal which has the highest energy at high frequencies when analyzed in critical bands. They tested high-frequency hearing losses. The choice of the test signal and the gain rule might have led to a particularly strong representation of signal energy in high-frequency critical bands, effectively reducing the bandwidth of the signal. This might be the reason, why they found reduced spectral loudness summation.
In [28] the same measurement procedure as in the present study was used to estimate spectral loudness summation. The authors found that monaural spectral loudness summation increased on average with increasing hearing thresholds. The subjects with asymmetrical hearing thresholds in that study had on average similar thresholds to the symmetrically HI subjects of the present study in their better ear. Consequently, in the present study, the hearing thresholds of the worse ear were higher than the average hearing thresholds of the symmetrically HI subjects. The higher hearing thresholds in the worse ear potentially result in larger spectral loudness summation based on the results of [28].
Binaural loudness summation of broadband signals was also found to be higher for HI subjects with N3 (moderate high frequency hearing loss) and S1 to S3 (very mild to moderate steep sloping hearing loss) audiometric configurations [51] compared to NH listeners [28]. For NH listeners, the average binaural summation of broadband signals was around 12 dB, whereas for patients with these configurations, the average binaural summation of broadband signals was 20 dB.
According to [52], the magnitude of binaural loudness summation in NH subjects varies with ILD, such that summation is maximal at an ILD of 0 dB and decreases with increasing ILD, so that the loudness evoked by stimuli with large ILDs resembles monaural loudness for the ear with the higher level. One could assume that the unbalanced levels of narrowband signals for the asymmetrically HI subjects with the HLC (Figure 6B) reduced binaural loudness summation. Unexpectedly, however, the loudness of binaural broadband noise for the asymmetrically HI listeners was higher than for the symmetrically HI listeners or NH listeners (Figure 3). Higher-than-normal binaural broadband loudness summation was previously reported for symmetrically HI subjects [27], [35]. The mechanisms behind the further increased binaural broadband loudness summation for asymmetrically HI listeners remain unclear.
It is common practice to measure loudness perception with monaural narrowband signals [2], [5], [53]. In this study, we found that monaural narrowband loudness compensation leads to different gains compared to those needed for a centered percept of binaural broadband signals, as found in [23]. Even with the knowledge that loudness compensation does not lead to a central percept, the individual variations in the present study were unexpectedly high. This implies that new methods for individual compensation are required. Asymmetric HLC that aims at optimizing loudness and at unbiased sound localization, cannot be successful by analyzing hearing loss with only monaural narrowband measurements. In a first step, the goals of hearing device fitting have to be defined more precisely. Since most people experience sounds in everyday life binaurally rather than monaurally, the fitting goals should be designed on the basis of a single binaural system and not on the basis of two independent ears. The fitting of subjects with a hearing aid on one ear and a cochlear implant on the other ear presents similar challenges but to an even larger extent (see [16], for a review). New developments and studies of HLC are needed for all types of asymmetric hearing loss.

Limitation

This study used a HLC method to compensate for the hearing loss. Methods to calculate gains from hearing thresholds are widely accepted in the field of hearing aid fitting. Well-known methods are NAL-NL2 and DSL v5, which are also used to calculate gains for asymmetric hearing losses. The exact calculations used by these procedures are not available to the public, but they have been evaluated in many studies. We validated our HLC rule by comparing it to available data. To derive the average loudness functions, we used the same procedure as described in [54], their Figure 6. However, there were many differences between the procedure in [54] and the procedure used in the present study. The categorical loudness scaling procedure of [54] used different headphones (insert earphones), different calibration (in-ear levels vs. coupler level), a different response scale, a different adaptive level procedure, and a different loudness function. Differences in categorical loudness scaling procedures lead to different loudness functions. That said, average gain functions measured with different categorical loudness scaling procedures can be compared as the average gain that is needed to restore normal loudness perception should be similar. We compared our gain estimation with the data published in [54] (their Figure 8). For 1 kHz, there is a visually good match with less than 3 dB deviation between both procedures. For 2 and 4 kHz, the pattern and the slopes of the gain functions were comparable, but the gain differences were more than 5 dB. The gain estimation method used in the present study led to lower gains than in [54]. Al-Salim et al. did not publish data for the frequencies 0.25, 0.5, and 6 kHz [54]. Thus, a comparison to their study was not possible for these frequencies.

Conclusions

Loudness, binaural fusion, lateralization and centralization with hearing-threshold-based narrowband loudness compensation was assessed in a series of psychoacoustic experiments for listeners with normal hearing, with symmetric hearing loss and with asymmetric hearing thresholds. From the results of these experiments, we conclude:

- For listeners with asymmetric hearing thresholds, hearing-loss compensation methods that aim at a central spatial percept when presenting broadband signals cannot be realized based on measurements of monaural hearing abilities and individual frequencies, or specific levels.
- There is a need for measurement procedures that compensate for hearing loss and lead to a central percept of binaurally presented broadband signals in the case of identical input levels.
- Previous conclusions for listeners with asymmetric hearing thresholds that were derived from monaural or narrowband measurements need to be revisited using binaural broadband measurement techniques.
- For listeners with asymmetric hearing thresholds new fitting procedures and validation methods for loudness, binaural fusion, and lateralization are required.

Data

Data for this article are available from PUBLISSO – Repository for Life Sciences (https://www.doi.org/10.4126/FRL01-006483142) [55].

Notes

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Competing interests

The authors declare that they have no competing interests.

Attachments

Available from https://doi.org/10.3205/zaud000045

1. Attachment1_zaud000045.pdf (113 KB)
   Tables 1–4, sections A1–A2

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