Characterizing individual hearing loss using narrow-band loudness compensation

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Loudness is one of the key factors related to overall satisfaction with hearing aids. Individual loudness functions can reliably be measured using categorical loudness scaling (CLS) without any training. Nevertheless, the use of loudness measurement like CLS is by far less common than use of audiometric thresholds to fit hearing aids, although loudness complaints are one of the most mentioned reasons for revisiting the hearing aid dispenser. A possible reason is that loudness measurements are typically conducted with monaural narrow-band signals while binaural broad-band signals as speech or environmental sounds are typical in daily life. This study investigated individual uncomfortable loudness levels (UCL) with a focus on monaural and binaural broad-band signals, as being more realistic compared to monaural narrow-band signals. Nine normal-hearing listeners served as a reference in this experiment. Six hearing-impaired listeners with similar audiograms were aided with a simulated hearing aid, adjusted to compensate the narrow-band loudness perception back to normal. As desired, monaural narrow-band UCLs were restored to normal, however large individual deviations of more than 30 dB were found for the binaural broad-band signal. Results suggest that broad-band and binaural loudness measurements add key information about the individual hearing loss beyond the audiogram.

INTRODUCTION

To compensate a hearing loss with multichannel dynamic compression, frequency- and level-dependent gains have to be adjusted to fit to the individual ear. The most common approach is to use audiogram-based fitting formulas, but still loudness complaints are one of the most mentioned reasons for revisiting the hearing aid dispenser (Jenstad *et al.*, 2003). The use of loudness measurements like categorical loudness scaling (CLS) is by far less common although individual supra-threshold information about the hearing loss can precisely be assessed (Brand and Hohmann, 2001). One reason might be that the typical monaural narrow-band test stimuli used in the CLS procedure are not suitable to describe the loudness perception of amplified binaural broad-band signals like speech as later processed by the hearing aid.

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However, so far no systematic measurements of binaural broad-band uncomfortable loudness levels (UCL) were conducted after hearing-impaired (HI) listeners were compensated for the monaural narrow-band loudness perception. In this study UCLs of signals with different bandwidth in monaural and binaural conditions were measured in HI listeners and compared with a normal-hearing (NH) group. The HI listeners had similar, typical age-related hearing losses and were aided with a simulated hearing aid that performed a static, frequency and level dependent amplification. The amplification was individually adjusted to restore the narrow-band loudness perception back to that of the NH control group.

METHODS

Nine younger NH (mean±std. age: 26.3±3.3 y) and six older HI (73.8±2.8 y) listeners participated in this study. All HI listeners had a high-frequency hearing loss and no self-reported tinnitus sensation. The HI listeners were selected to have similar hearing threshold levels as shown in Fig. 1. The PTA (500, 1k, 2k, and 4k) was between 30 and 44 dB HL.
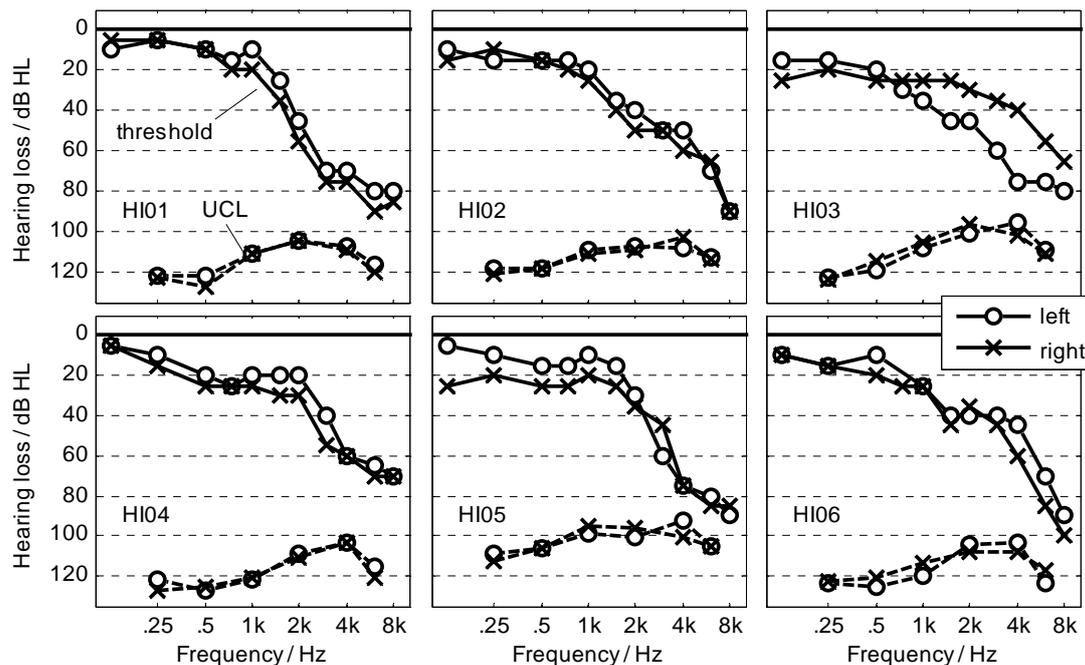

Fig. 1: Audiograms of the six HI listeners with high frequency hearing losses. Subjects were selected to have similar hearing threshold levels. The bottom lines in each panel show the uncomfortable loudness levels (UCL) corresponding to the level for "too loud" (50 CU) on the loudness function.

All subjects conducted the adaptive categorical loudness scaling procedure (ACALOS; Brand and Hohmann, 2002) with one-third octave signals (low-noise noise, LNN) at six center frequencies (250, 500, 1k, 2k, 4k, and 6k). Three repetitions on at least two different days were performed. The stimulus duration was 1000 ms. The uncomfortable loudness levels (UCL) for "too loud" (50 categorical units; CU) of the LNN signals were extracted and are included at the bottom of each panel in Fig. 1. The narrow-band loudness functions were used to provide each HI listeners with a narrow-band loudness compensating algorithm where the average loudness functions of the NH listeners served as the target loudness function for the gain calculations. The method for gain calculation is shown in Fig. 2. The channel levels of an input signal were determined in six channels having the same center frequency as the LNN signals as shown in Fig. 2a. The gain calculation for the 2-kHz channel for subject HI02 is shown in Fig. 2b. The narrow-band NH loudness corresponding to the channel level was determined (black vertical line in Fig. 2b) and the required gain to restore the narrow-band loudness back to normal was extracted (horizontal black line, 23.5 dB). The gain values at each center frequency were interpolated on a logarithmic frequency and on a logarithmic level axis and applied to the input signal as static gains in the frequency domain (Fig. 2c).
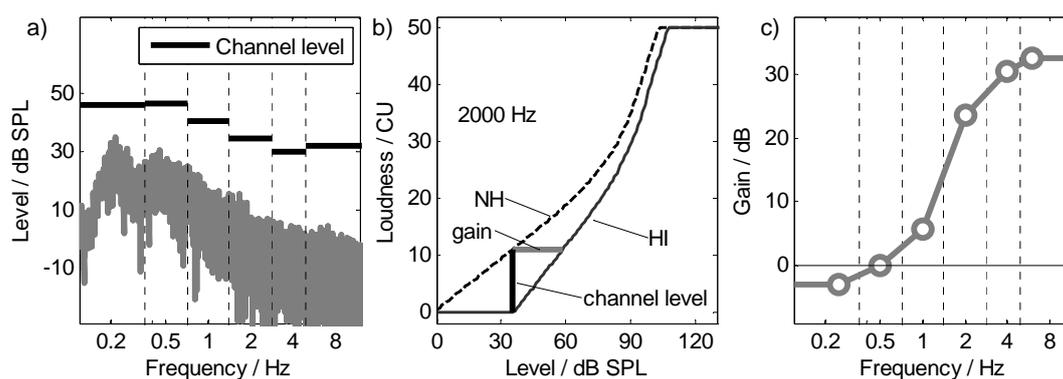

Fig. 2: Gain calculation for narrow-band loudness compensation using listener HI02 as example: a) Channel levels in six channels of the IFnoise at 50 dB SPL; b) gain values were extracted from the difference between the average NH loudness function (dashed) and the individual loudness function (solid); c) gains values were interpolated on a logarithmic frequency axis and applied in the frequency domain for the left and right ear independently.

UCLs were measured in NH and narrow-band loudness compensated HI listeners for different test signals. As test signals uniform exciting noise (UEN) with 1- and 5-Bark bandwidth and a speech-shaped noise (international female noise, IFnoise) were used. The Bark spectra of these signals are shown in Fig. 3a. Loudness scaling measurements to extract the UCL was conducted for monaural and binaural presentation. Three repetitions on at least two different days were performed. For data analysis, the differences of the UCL compared to the mean NH listeners (ΔUCL) were assessed as shown in Fig. 3b.
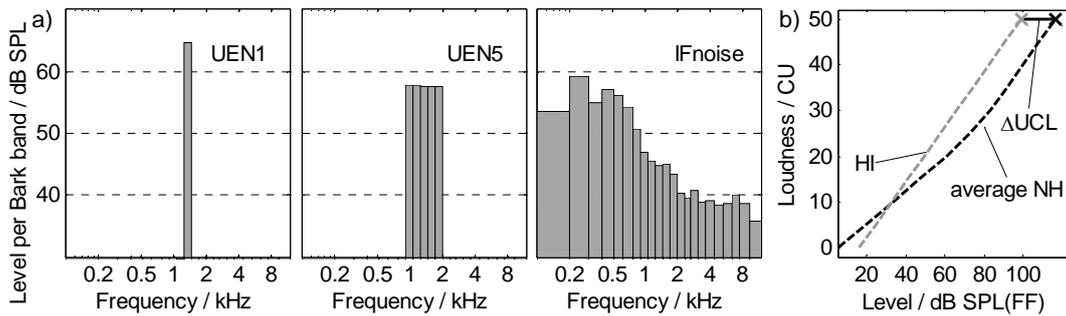
Fig. 3: a) Bark spectrum of the test signals; b) The difference of the UCL at 50 CU compared to the mean NH values (ΔUCL) was extracted and used for further data analysis.

All measurements were conducted with Sennheiser HDA200 headphones in a sound-proof both. Signals were presented using an RME Fireface UC at 44.1 kHz and a Tucker-Davis HB7 headphone driver. Headphones were calibrated using the B&K artificial ear 4153, B&K 0.5-inch microphone 4134, B&K microphone preamplifier 2669, and B&K measuring amplifier 2610. Signals were calibrated using the free-field equalization according to ISO 389 (2004). The maximum presentation level was 105 dB HL for the LNN signals and 105 dB SPL for the test signals (UEN1, UEN5, and IFnoise).

RESULTS

UCL differences are shown for each HI listener on a 2D map in Fig. 4 with the three test signals on the x-axis with increasing bandwidth (UEN1, UEN5, IFnoise) and the presentation mode (left, binaural, right) on the y-axis. The grayscale-coded map shows the difference between the UCL of the average NH listener and the individual measured UCL (ΔUCL). Measurement points are indicated by the white circles whereas all other pixels are interpolated to facilitate visual accessibility.

The scaling bar at the right side of the figure shows the absolute values of the grayscale. Light gray correspond to values around 0 dB, meaning that the compensated UCL is very similar compared to the average NH UCL. Dark gray indicates lower and lighter gray indicates higher UCLs compared to the average NH listeners. Each 5 dB step is indicated by black contour lines including figures of the absolute amount of ΔUCL.

The narrow-band UEN1 signal for the left and right condition results in light gray colors (top and bottom left corner of each panel) for all HI listeners. The restored monaural narrow-band UCLs were close to the average NH UCL. This confirmed that the gains from the narrow-band loudness compensation rule were appropriately set, at least around the center frequency of the UEN1 noise (1370 Hz). For most listeners, similar UCL values were also observed in the binaural condition for UEN1, but two

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listeners (HI01 and HI03) showed lower UCLs indicated by the darker gray towards the middle of the left edge of each 2D map. With increasing bandwidth of the test signals, the differences between listeners further increased. ΔUCL values for the binaural IFnoise condition (middle point of the right edge of each panel) were between −30 dB (HI01, HI03) and around 0 dB (HI05, HI06). Listeners HI02 and HI04 showed ΔUCL values around 0 dB in the for the monaural IFnoise condition, but ΔUCL values decreased to −10 and −15 dB in the binaural IFnoise condition.
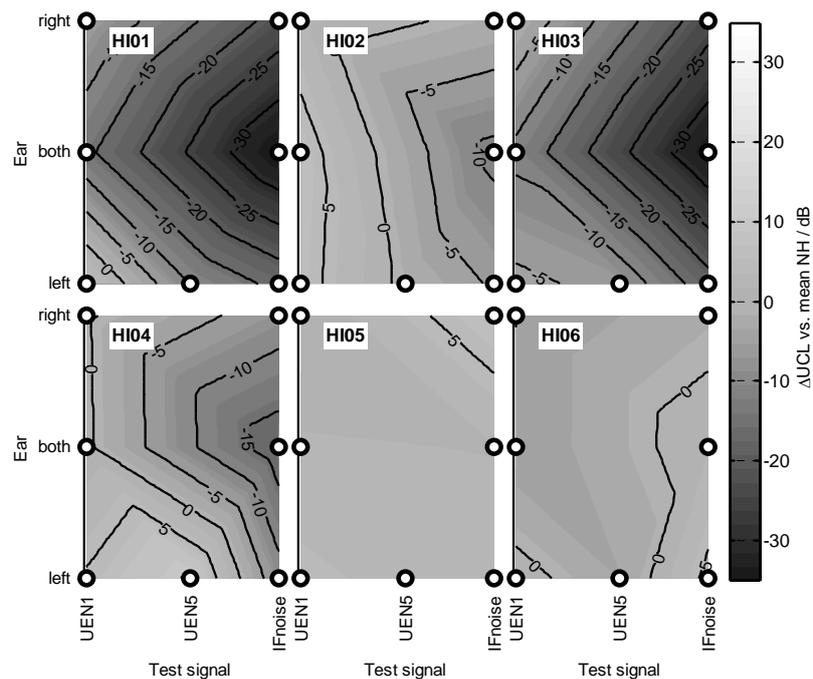

Fig. 4: Grayscale coded ΔUCL values indicate the level difference between individual UCL values after loudness compensation and the average NH UCL values. Large individual variabilities were observed: i) Similar values as for NH listeners were found in HI05 and HI06; ii) Lower UCL values for monaural and binaural broad-band signals were found in listeners HI01 and HI03; and iii) lower UCL values in the binaural broad-band case but not in the monaural case were observed in listeners HI02 and HI04.

Figure 5 shows the same 2D maps of ΔUCLs comparing individual NH listeners to the average NH listener. Overall, the ΔUCL values are within a ±10 dB range except for NH04 who showed up to 20 dB higher UCL values compared with the average NH listener.

Comparison of the results for the NH and the HI listeners indicates that individual variations were considerably higher in the narrow-band loudness compensated HI listeners than in the NH control group.
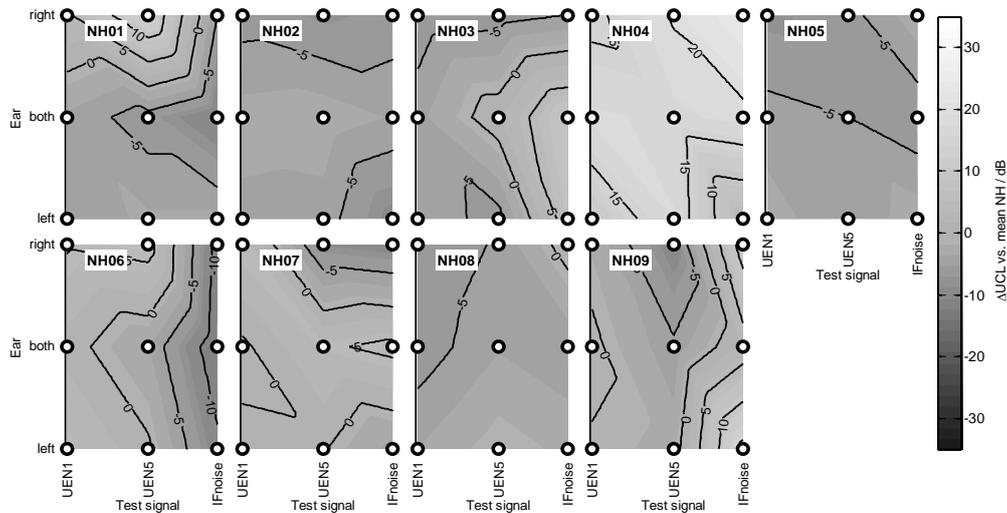
Fig. 5: Same as Fig. 4 but for the NH listeners. Individual variations were lower compared to the HI listeners.

DISCUSSION

After narrow-band, monaural loudness perception was compensated for in HI listeners, large individual variations in the uncomfortable loudness level (UCL) were observed for other types of signals. Especially for binaural broad-band test signals the UCL was lowered by up to 30 dB whereas other HI listeners showed totally normal UCL values.

Bentler and Pavlovic (1989) showed an increased amount of spectral loudness summation of tone complexes at the UCL in HI listeners compared to NH listeners. Furthermore, an increasing amount of individual variations was indicated by increased standard deviations compared to a NH group, but they tested only monaurally. Surprisingly, several subjects in the current data showed a decrease of more than 10 dB of the UCL value for the broad-band signal when comparing the monaural with the binaural presentation. This means that gains which were adjusted for the correct loudness perception in the left and right ear, separately, can be too high for loudness compensation if they are used in a bilateral presentation mode. Increased loudness sensitivity was found by Smeds *et al.* (2006), where hearing aid gains were adjusted according to NAL-NL1 which should led to normal or lower-than-normal loudness (Byrne *et al.*, 2001). The aided HI listeners rated the loudness higher than the NH listeners for broadband binaural signals with medium to high input levels. These observations are in line with the current data. Furthermore, Smeds *et al.* (2006) already speculated that there might be a problem with the underlying loudness model in NAL-NL1. The underlying loudness model is a monaural loudness model (Moore and Glasberg, 1997) which cannot account for an altered binaural summation in HI listeners. Keidser *et al.* (2012) mentioned that about 45% of the subjects preferred

lower gains than prescribed by NAL-NL1. The successor fitting rule NAL-NL2 includes the empirical insights and therefore further reduces the prescribed gains. These gain adjustments might be more suitable for normal loudness of binaural broad-band signals, but do not consider the individual variations of binaural broad-band UCLs as found in the current data. Because of the similar hearing thresholds of the HI listeners the prescribed gains would be quite similar by fitting formulas based on the hearing threshold.

The current binaural broad-band UCL measurements might contain valuable information for hearing-aid fitting or the diagnosis of the underlying pathology. Until now, no binaural broad-band UCL measurement is included in standard clinical protocols, e.g., to determine the remaining dynamic range for broad-band binaural signals. Considering the observed large individual variability in the six subjects, it is obvious that no listener-independent correction factor for binaural presentation could be determined.

A possible reason for the increased loudness perception might be an increased central gain of the auditory system as reported for NH listeners with tinnitus by Schaette and McAlpine (2011). They measured brainstem responses in NH subjects with tinnitus compared to a NH control group and found reduced auditory-brainstem-response wave I (evoked from auditory nerve) in the tinnitus groups whereas there was no difference in wave V (evoked from inferior colliculus) between both groups which indicates an increased central gain in tinnitus patients. Qiu *et al.* (2000) found an increased auditory cortex potential in chinchillas after inner hair cell loss although the compound action potential elicit by the auditory nerve was reduced.

It remains unclear how such a potential central gain mechanism in HI listeners is realized in the auditory pathway as the increased gains based on the observed UCL differences in the HI listeners can be quite different between narrow- and broad-band signals but also for monaural and binaural presentation.

AKNOWLEDGMENTS

REFERENCES

Bentler, R.A. and Pavlovic, C.V. (**1989**). "Comparison of discomfort levels obtained with pure tones and multitone complexes," J. Acoust. Soc. Am., **86**, 126-132.

Brand, T. and Hohmann, V. (**2001**). "Effect of hearing loss, centre frequency, and bandwidth on the shape of loudness functions in categorical loudness scaling," Int. J. Audiol., **40**, 92-103.

Brand, T. and Hohmann, V. (**2002**). "An adaptive procedure for categorical loudness scaling," J. Acoust. Soc. Am., **112**, 1597-1604.

Byrne, D., Dillon, H., Ching, T., and Katsch, R. (**2001**). "The NAL-NL1 procedure for fitting non-linear hearing aids: Characteristics and comparisons with other procedures," J. Am. Acad. Audiol., **12**, 37-51.

Jenstad, L.M., Van Tasell, D.J., and Ewert, C. (**2003**). "Hearing aid troubleshooting based on patients' descriptions," J. Am. Acad. Audiol., **14**, 347-360

Keidser, G., Dillon, H., Carter, L., and O'Brien, A. (**2012**). "NAL-NL2 empirical adjustments," Trends Amplif., **16**, 211-223.

Moore, B.C.J. and Glasberg, B.R. (**1997**). "A model of loudness perception applied to cochlear hearing loss," Audit. Neurosci., **3**, 289-311.

Qiu, C., Salvi, R., Ding, D., and Burkard, R. (**2000**). "Inner hair cell loss leads to enhanced response amplitudes in auditory cortex of unanesthetized chinchillas: evidence for increased system gain," Hear. Res., **139**, 153-171.

Schaette, R. and McAlpine, D. (**2011**). "Tinnitus with a normal audiogram: physiological evidence for hidden hearing loss and computational model," J. Neurosci., **31**, 13452-13457.

Smeds, K., Keidser, G., Zakis, J., Dillon, H., Leijon, A., Grant, F., Convery, E., and Brew, C. (**2006**). "Preferred overall loudness. I: Sound field presentation in the laboratory," Int. J. Audiol., **45**, 2-11.