Spectral and binaural loudness summation in bilateral hearing aid fitting

MAARTEN VAN BEURDEN[1,2], MONIQUE BOYMANS[1,2], MIRJAM VAN GELEUKEN[1], DIRK OETTING[3], AND WOUTER A. DRESCHLER[1,*]

[1] *Academic Medical Center, Department of Clinical & Experimental Audiology, Amsterdam, The Netherlands*

[2] *Libra Rehabilitation & Audiology, Eindhoven, The Netherlands*

[3] *HörTech gGmbH and Cluster of Excellence Hearing4all, Oldenburg, Germany*

Aversiveness of loud sounds is a frequent complaint by hearing-aid users, especially when fitted bilaterally. This study investigates whether loudness summation can be held responsible for this finding. Two aspects of loudness summation should be taken into account: spectral loudness summation for broadband signals and binaural loudness summation for signals that are presented binaurally. In this study different aspects were investigated: (1) the effect of different symmetrical hearing losses according to the classification of Bisgaard *et al.* (2010): N2, N3, N4, S2, and S3, and (2) the effect of spectral shape of broadband signals, by using high frequency noise and low frequency noise. For the measurements we used a well-standardized technique "Adaptive Categorical Loudness Scaling" (ACALOS). Also loudness matching was applied as a potentially clinical technique to get information about the individual loudness perception. Results show large individual differences in binaural loudness perception especially for broadband stimuli.

INTRODUCTION

Nowadays, the majority of listeners with hearing loss are fitted bilaterally. The use of two hearing aids increased over the last decades and reached values of about 75% in the US (Kochkin, 2009) and about 70% in Europe (see www.ehima.com). Bilaterally fitted hearing aids have been shown to improve speech intelligibility both in quiet and in noise and to improve localization (Boymans *et al.*, 2008; 2009). However, with respect to aversiveness of loud sounds bilateral fittings typically have poorer scores than unilateral fittings (Boymans *et al.*, 2009). Loudness complaints remain a major reason for revisiting the hearing aid dispenser (Jenstad *et al.*, 2003) and averseness of loud sounds is one of the main reasons to be dissatisfied with a hearing aid fitting (Hickson *et al.*, 2010).

It is generally accepted that hearing aid rehabilitation involves successive steps, starting with a first-fit based on a prescriptive formula, followed by individual fine tuning based on subjective responses and/or technical measurements using in-situ responses.

---

*Corresponding author: w.a.dreschler@amc.uva.nl

Proceedings of the International Symposium on Auditory and Audiological Research (Proc. ISAAR), Vol. 6: Adaptive Processes in Hearing, August 2017, Nyborg, Denmark. Edited by S. Santurette, T. Dau, J. C.-Dalsgaard, L. Tranebjærg, T. Andersen, and T. Poulsen. The Danavox Jubilee Foundation, 2017. ISBN: 978-87-990013-6-1.

Over the years a number of prescriptive formulas have been developed. The linear prescriptive formulas (e.g., NAL-R) have been replaced by non-linear prescriptions as NAL-NL2 (Dillon, 2012), taking into account that the amount of gain required is not only frequency dependent, but also level dependent.

Nonlinear fitting formulas show some relationship with the loudness growth at different frequencies. The level of detail of knowledge about loudness perception required for an effective first-fit setting is still in debate. But the dynamic range as the frequency-dependent range between the individual thresholds and the levels of uncomfortable loudness is generally accepted and applied in different forms in nonlinear prescriptive formulas.

Due to the fact that the hearing loss is often strongly frequency-dependent, loudness growth is usually measured with narrow-band signals. Loudness curves measured in individual hearing-impaired subjects can be compared with loudness curves of normal-hearing listeners and thus transferred into level-dependent gain prescriptions for hearing aid amplification settings to normalize loudness (Herzke and Hohmann, 2005).

However, in this approach, two aspects of loudness perception are not taken into account: spectral loudness summation (in case of the presentation of broadband signals instead of narrow-band signals) and binaural loudness summation (in case of bilateral presentation instead of unilateral). This includes also the binaural loudness perception of broadband signals which can be referred to as binaural spectral loudness summation. This combined effect has to be considered because typically two hearing aids are worn and they will typically process broadband signals as speech or environmental sounds.

These three types of loudness summation may require individual corrections. Recent data of hearing-impaired listeners (Oetting *et al.*, 2016) showed large individual differences in spectral loudness summation and binaural loudness summation after careful narrowband loudness normalization. Some of the listeners showed loudness perception for binaural broadband signals that was fully in agreement with normal-hearing reference data whereas others showed a higher-than-normal loudness sensitivity of up to 30 dB SPL for the binaurally presented broad-band signals. Given the magnitude of the inter-individual differences found, it can be assumed that these findings are relevant for loudness adjustments during bilateral hearing aid fittings.

In this study we measured spectral and binaural loudness summation as well as the combination, binaural spectral loudness summation. Listeners with different audiometric shapes were tested to investigate if the shape of the audiogram could explain the individual differences.

METHODS

Subjects

The inclusion criteria were: Age above 18 years; Native speaker of Dutch.

From the clinical files we selected subjects with mild to moderate symmetrical hearing losses (differences between both ears at 0.5, 1, 2 and 4 kHz < 10dB) and their pure-tone audiograms were classified according to Bisgaard *et al.* (2010). Twelve women and 10 men participated with an average age of 70 years. The classifications of the audiograms of the 44 ears included can be seen in Fig. 1.

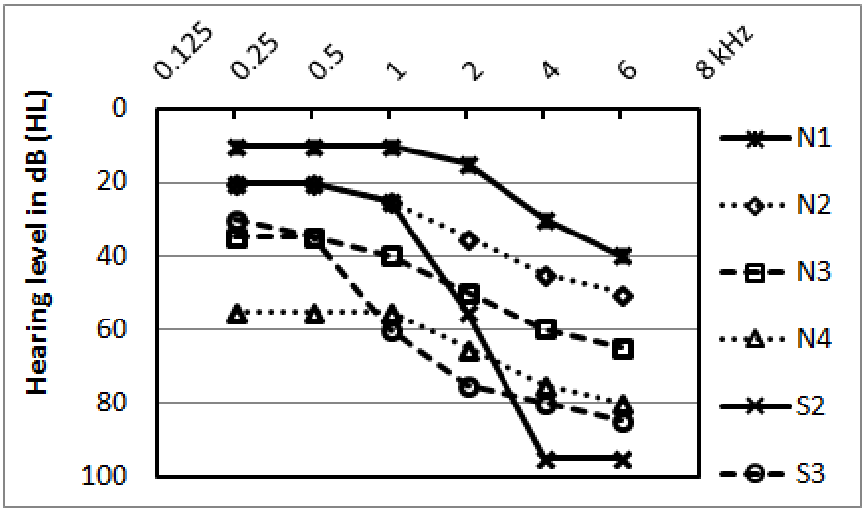


Fig. 1: Standard audiograms according to Bisgaard *et al.* (2010). There are 1, 11, 18, and 6 ears in the categories N1 to N4, and 6 and 2 ears in categories S2 and S3, respectively.

Equipment

All measurements were conducted in a sound-insulated booth in two sessions of about 2 hours each. Pure-tone audiograms (air and bone conduction) were measured with DECOS audiometers, using TDH39 headphones. Sennheiser HDA 200 headphones were used for the loudness scaling and the loudness matching. Both procedures were conducted using the framework for psychoacoustic experiments (Ewert, 2013). Signals were presented using a RME Fireface UC at 44.1 kHz. Headphones were calibrated using a Brüel & Kjær artificial ear type 4153, a 0.5-inch microphone type 4134, a microphone preamplifier type 2669, and a measuring amplifier type 2610. Headphones were free-field equalized according to ISO 389 (2004) and levels are expressed as the equivalent free-field level in dB SPL(FF).

Stimuli

All stimuli were 1-s noises with 50-ms rise and fall ramps. For the narrow-band signals one-third octave low-noise noises (LNN; Kohlrausch *et al.*, 1997) were used. The narrow-band stimuli had center frequencies of 250, 500, 1000, 2000, 4000, and 6000 Hz. The stimuli to assess loudness summation effects consisted of uniformly exciting noise (UEN, Fastl and Zwicker, 2007) with bandwidths of 1, 5, and 17 Barks, referred to as UEN1 (bandwidth: 210 Hz), UEN5 (1080 Hz) and UEN17 (5100 Hz), respectively. The UEN noises were centered at 10.5 Bark (1370 Hz).

In addition to the UEN noises a speech shaped noise referred to as IFnoise (international female noise) was included in the test battery. The IFnoise was generated to match the spectral shape as the long-term average speech spectrum for females (Byrne *et al.*, 1994).

Loudness Scaling Procedure

After the inclusion criteria were checked, categorical loudness scaling using ACALOS was performed to measure the individual loudness perception. During the ACALOS procedure listeners had to rate the perceived loudness on an 11-point scale from “not heard” to “too loud”, which were transformed into numerical values in “Categorical Units” (CU) from 0 to 50. Stimuli were presented in a pseudo-random order with levels between −10 and 105 dB HL. A monotonically increasing loudness function was fitted to the responses for each of the ACALOS measurements using the BTUX fitting method (Oetting *et al.*, 2014). The model function consists of two linear parts with independent slopes m_{low} and m_{high} with a smooth transition range (see Brand and Hohmann, 2002).

Before loudness summation was determined for the broadband signals the UEN and IFnoise noises were corrected for each hearing impaired subject individually aiming to restore the loudness of the narrow-band signals to that of the average normal hearing listener (narrow-band loudness normalization). The required gain (Fig. 2) was defined as the difference in level for each loudness category between the individual loudness functions of the narrow-band signals and the average normal hearing loudness function. To quantify the level of correction, for each narrow-band signal the compression ratio (CR) was calculated defined as the ratio between input and output level at 40 and 80 dB input level according to:

$$CR = \frac{\Delta in}{\Delta out} = \frac{\Delta in}{\Delta in - \Delta gain} = \frac{80-40}{80-40-(G40-G80)} = \frac{40}{40-\Delta gain} \qquad Eq. (1)$$

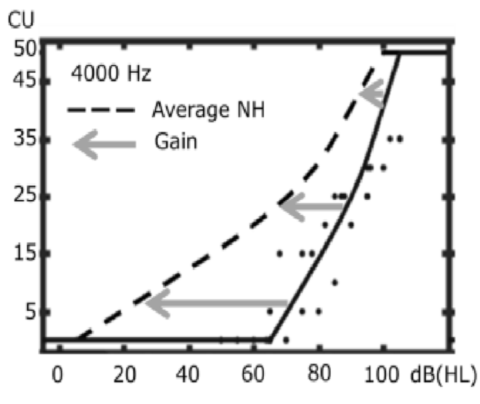


Fig. 2: Gain correction at 4000 Hz to the normal-hearing reference.

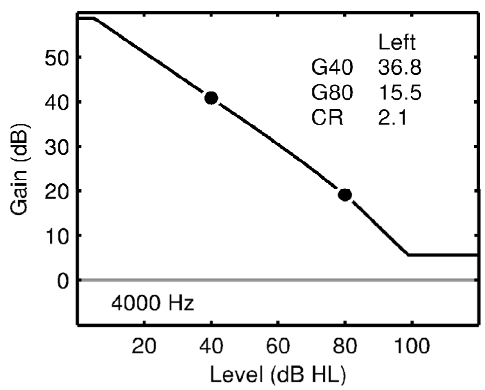


Fig. 3: Compression ratio of 2.1, calculated for the 4 kHz signal of Fig. 2.

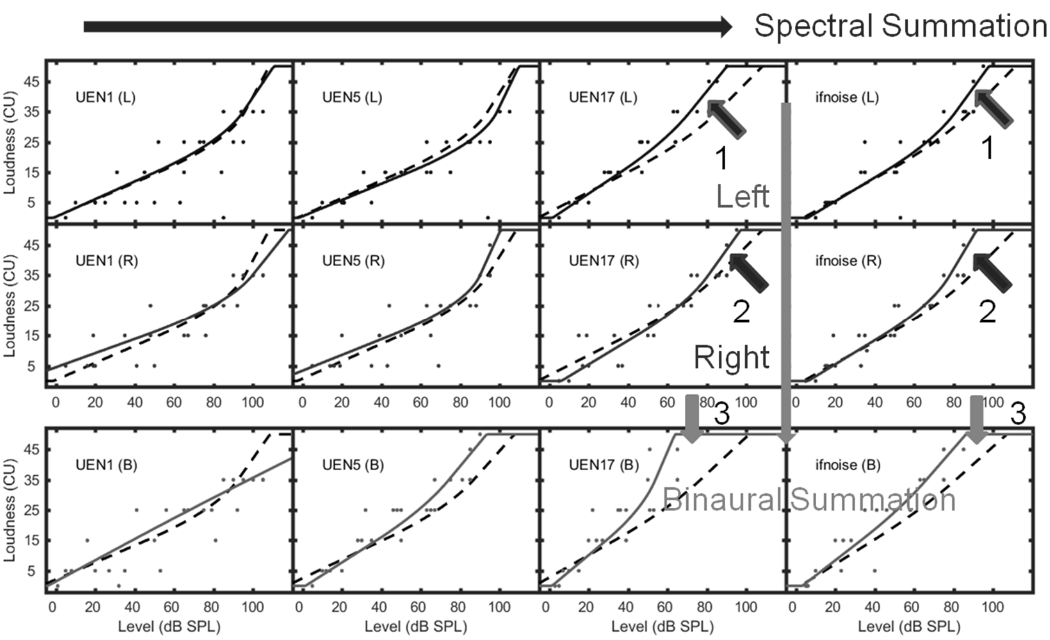
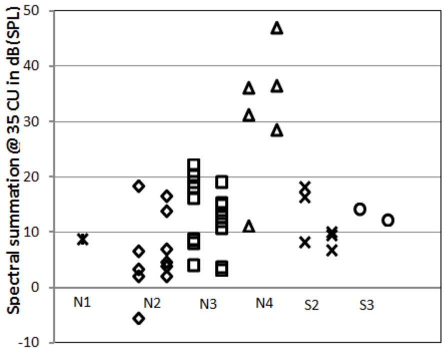


Fig. 4: Results for a hearing-impaired listener for spectral loudness summation for signals with increasing bandwidth (from left to right) and binaural loudness summation: from unilateral (upper rows) to bilateral (bottom row) presentation.

RESULTS

The narrow-band loudness normalization fitting method showed decreasing gains with increasing presentation level (Fig. 3). The results show that this fitting was able to restore normal loudness perception of narrow-band signals (UEN1, left panels in Fig. 4). However, normal loudness perception for narrow-band signals is no guarantee for normal loudness perception for broadband and binaurally presented signals, in fact, huge inter-individual variability was found in these conditions. Examples of such differences are shown in Fig. 4. In Fig. 4 spectral loudness summation (with increasing bandwidth from left to right) is shown to be higher than normal at high levels for both UEN17 and IFnoise at both ears (see arrows 1 and 2). In the same subject binaural spectral loudness summation (lower panel) for these same stimuli is even higher (arrows 3).

Figure 5a shows individual data per ear for the differences in spectral loudness summation at 35 CU (calculated as the level differences of the average level of UEN17 and IF noises relative to the average level of UEN1 and UEN5). Even within a Bisgaard classification large inter-individual differences in loudness summation were found. The differences between hearing loss configurations suggest a trend for more spectral loudness summation for hearing impaired subjects with increasing hearing loss, especially at configuration N4. Figure 5b shows the binaural loudness



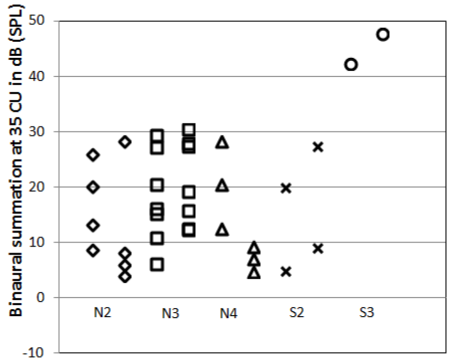
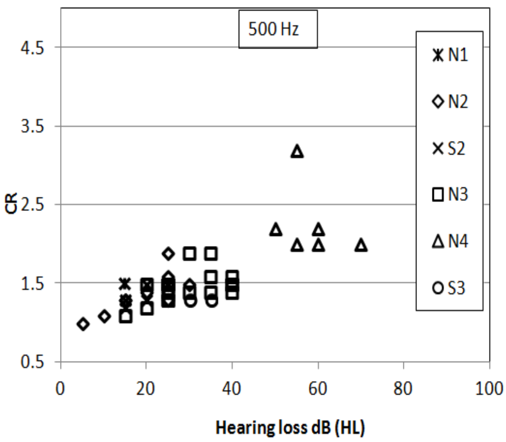


Fig. 5: Individual spectral loudness summation (5a) and binaural loudness summation (5b) per ear. Left hand side: left ear. Right hand side: right ear.



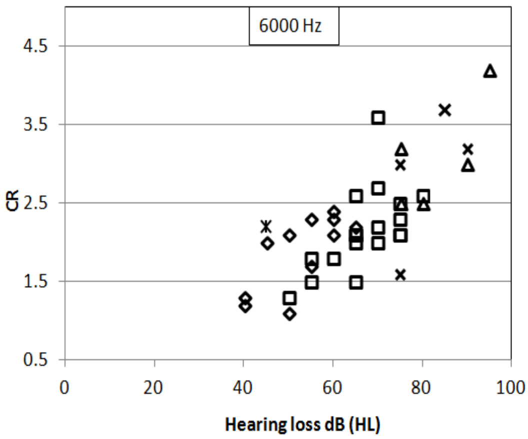


Fig. 6: Compression ratios for all subjects at 500 Hz (left panel) and at 6000 Hz (right panel) for different hearing loss categories.

summation effect (calculated as the level differences of the average binaural UEN 17 and IF noises relative to the average level of the monaural UEN17 and IF noises for both ears individually) as a function of hearing loss configuration. For binaural loudness summation the group data are more uniform across different audiogram configurations. However, we also found an extreme high level of binaural loudness summation for the single subject with hearing loss configuration S3.

Figure 6 shows the calculated CRs per ear for different hearing loss categories for narrow-band signals at 500 Hz and 6000 Hz. At both frequencies CRs tend to increase with increasing hearing losses. The CRs at 6000 Hz are higher than at 500 Hz, not only due to the fact that the hearing losses in the higher frequencies are on average higher, but also due to the fact that the increase of CR with increasing hearing loss tends to be stronger at 6000 Hz than at 500 Hz. CRs may therefore be used to characterize the amount of loudness compensation used in a certain narrow-band region.

DISCUSSION AND CONCLUSIONS

Although narrow-band loudness normalization has proven to give good individual results for narrowband signals, the current results show that this does not guarantee loudness normalization for broadband stimuli or stimuli presented binaurally. Furthermore, the large individual variability of spectral and binaural loudness summation could not be predicted from the hearing loss configuration. The only observed trends were higher spectral loudness summation in listeners with N4 audiograms and higher binaural loudness summation in a subject classified as S3.

In further analysis the compression ratios may be useful to investigate if the amount of loudness summation can be predicted by the amount of loudness compensation (applied gain for broadband signals).

The high individual variability in loudness perception for binaurally presented broadband signals can be one of the causes of aversiveness for loud sounds of bilateral hearing aid users. The individual differences are that large that they should be taken into account during the hearing aid fitting procedure. Currently, the most common fitting rules only utilize average gain corrections for bilateral fittings that are identical for all hearing-impaired subjects. NAL-NL1 and NAL-NL2 utilize a bilateral compensation (reduction in gain) with respect to a unilateral fitting of 3 and 2 dB, respectively, for input levels below 40 dB increasing to 6 and 8 dB, respectively at 90 dB SPL and above. (Byrne *et al.*, 2001; Keidser *et al.*, 2012). Our results show bilateral summation effects above 20 dB at high levels.

Therefore, there is a need to adjust fitting rules for bilaterally fitted hearing aids to take the large individual differences in loudness summation into account. A loudness-based approach based on individual measurements will require extra tests and thus requires extra time that is usually scarce. For this purpose we compared loudness matching with loudness scaling to find out if the first method is applicable in clinical practice and can be used as an alternative with reduced testing time. Preliminary results indicate that loudness matching could be suitable. A typical loudness scaling condition takes about 2 minutes. A single comparison between conditions therefore takes about 4 minutes. The loudness matching procedure compares 15 conditions in about 10 minutes.

More important is that the loudness matching produces about equivalent results to the loudness scaling data. That is, in one and the same subject, the amount of loudness difference between two stimuli (narrow-band vs. broad-band and monaural vs. binaural) at 35 CU is in qualitative agreement in both procedures.

REFERENCES

Bisgaard, N., Vlaming, M.S., and Dahlquist, M. (**2010**). “Standard audiograms for the IEC 60118-15 measurement procedure,” Trends Amplif., **14**, 113-120.

Boymans, M., Goverts, S.T., Kramer, S.E., Festen, J.M., and Dreschler, W.A. (**2008**). “A prospective multi-centre study of the benefits of bilateral hearing aids,” Ear Hearing, **29**, 930-941.

Boymans, M., Goverts, S.T., Kramer, S.E., Festen, J.M., and Dreschler, W.A. (**2009**). "Candidacy for bilateral hearing aids: a retrospective multicenter study," J. Speech Lang. Hear. Res., **52**, 130-140.

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

Byrne, D., Dillon, H., Tran, K., Arlinger, S., Wilbraham, K., Cox, R., Hagerman, B., *et al.* (**1994**). "An international comparison of long-term average speech spectra," J. Acoust. Soc. Am., **96**, 2108-2120.

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

Dillon, H. (**2012**). *Hearing Aids Second Edition.* Sydney, Australia: Boomerang Press, pp. 226.

Ewert, S.D. (**2013**). "AFC – a modular framework for running psychoacoustic experiments and computational perception models," 39 Tagung der Deutschen Arbeitsgemeinschaft für Akustik (DAGA).

Fastl, H., and Zwicker, E. (**2007**). In: *Psychoacoustics: Facts and Models, third ed.* Springer, Berlin.

Herzke, T., and Hohmann, V. (**2005**). "Effects of instantaneous multiband dynamic compression on speech intelligibility," EURASIP J. App. Sig. P., **18**, 3034-3043.

Hickson, L., Clutterbuck, S., and Khan, A. (**2010**). "Factors associated with hearing aid fitting outcomes on the IOI-HA," Int. J. Audiol., **49**, 586-595.

ISO 389-8 (**2004**). *Acoustics - Reference zero for the calibration of audiometric equipment.*

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

Kochkin, S. (**2009**). "MarkeTrak VIII: 25-year trends in the hearing health market," Hearing Review, **16**, 12-31.

Kohlrausch, A., Fassel, R., van der Heijden, M., Kortekaas, R., van de Par, S., Oxenham, A.J., and Püschel, D. (**1997**). "Detection of tones in low-noise noise: Further evidence for the role of envelope fluctuations," Acta Acust. United Ac., **83**, 659-669.

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.

Oetting, D., Brand, T., and Ewert, S.D. (**2014**). "Optimized loudness-function estimation for categorical loudness scaling data," Hear. Res., **316**, 16-27.

Oetting, D., Hohmann, V., Appell, J.-E., Kollmeier, B., and Ewert, S.D. (**2016**). "Spectral and binaural loudness summation for hearing-impaired listeners," Hear. Res., **335**, 179-192.