Analyzing the effects on the internal signal-to-noise ratio for bilateral hearing-aid systems configured for asymmetric processing

FREDRIK GRAN[1,*], JESPER UDESEN[1], TOBIAS PIECHOWIAK[1], AND ANDREW B. DITTBERNER[2]

[1] *GN ReSound A/S, Lautrupbjerg 7, DK-2750 Ballerup, Denmark*

[2] *GN ReSound North America, 8001 Bloomington Freeway, Bloomington, MN 55420-1036, USA*

This paper investigates how bilateral hearing-aid systems configured to perform asymmetric processing affect the internal signal-to-noise ratio (SNR) in the auditory system. Here, an asymmetric hearing-instrument (HI) system is characterized by directional noise reduction in the instrument in one ear whereas the contra-lateral device is adjusted for omni mode processing. The Equalization and Cancellation model is used to evaluate the internal SNR of the auditory system. Two reference conditions were also created, a system with directionality in both HI, and one with omni-mode processing in both HI. A speaker was placed to the front, and another speaker was placed at the side. In the first experiment, the target was assumed to be in the front direction and the noise was assumed to be coming from the side. Here, it was shown that the asymmetric system provided the same SNR as the system with directionality in both HI. The noise and target positions were interchanged and the experiment was repeated. In this case, the asymmetric system provided similar SNR as the system with omni-mode processing in both HI, which for this test condition provided a better SNR than the system with directionality in both HI.

INTRODUCTION

Directional hearing-aid systems have been shown to improve speech intelligibility in noisy conditions (Ricketts and Dittberner, 2002). Directionality algorithms and/or technologies aim at preserving signals originating from the look direction (0 degrees) whilst suppressing sources from all other directions. In digital dual-microphone systems this is typically done by placing a null in a direction where the masker is assumed to be located. An inherent aspect of this processing strategy is that the listener loses sensitivity to sources to the side and in the back as compared to single microphone systems (omni-mode processing). Asymmetric processing schemes (omni mode in one ear and directional technology in the contralateral ear) have been shown to provide similar speech understanding performance for hearing-impaired subjects as when applying symmetrically configured hearing aids programmed to

*Corresponding author: fgran@gnresound.com

Proceedings of ISAAR 2013: Auditory Plasticity – Listening with the Brain. 4th symposium on Auditory and Audiological Research. August 2013, Nyborg, Denmark. Edited by T. Dau, S. Santurette, J. C. Dalsgaard, L. Tranebjærg, T. Andersen, and T. Poulsen. ISBN: 978-87-990013-4-7. The Danavox Jubilee Foundation, 2014.

provide directionality towards the front (Bentler *et al.*, 2004; Cord *et al.*, 2005). In both these studies, the target signal was originating from the front and the masker signals were originating from other directions, playing mutually uncorrelated speech-shaped noise. Both papers showed no significant difference between the asymmetric processing condition and the symmetric directionality condition. In Hornsby and Ricketts (2007), several target and masker configurations were investigated, 1) target in front and five masker sources evenly distributed in a circle around the listener, 2) target to the front and five masker sources evenly distributed between 50°-130° and 3) target at 90° and three masker sources evenly distributed between 45°-135°. The purpose was to mimic listening in diffuse noise with configuration 1, listening to a target in front with interferers coming predominantly from the left in configuration 2, and trying to concentrate on a talker to the right with the majority of the masker energy coming from the left in condition 3. The hearing aids were programmed for symmetric omni-mode processing, symmetric directionality processing, and asymmetric processing. Both symmetric directionality and asymmetric processing showed a benefit on speech reception thresholds (SRT) compared to symmetric omni-mode processing for conditions 1 and 2, whereas a performance degradation was observed for condition 3. The SRT degradation was found to be smaller for the asymmetric processing compared to the symmetric directionality processing when the hearing instrument programmed for omni-mode processing faced away from the masker sources.

The purpose of this paper was to investigate if binaural listening models can predict these phenomena. In particular, the Equalization and Cancellation (EC) model (Kock, 1950; Durlach, 1960, 1963) was used to model the binaural signal-to-noise ratio (SNR) of the auditory system for different target and masker conditions as well as different hearing-aid processing configurations. The EC model was proposed to model the binaural masking level differences (BMLD) of detecting tones in noise for dichotic vs diotic signal presentation. This model was later modified and used to explain several data sets for more complicated listening experiments, such as modeling speech-intelligibility improvement for speech masked by a single noise source in an anechoic space (Zurek, 1992), speech-intelligibility improvements in multi-talker speech-shaped interference in an anechoic space (Culling *et al.*, 2004), speech-intelligibility tasks in anechoic and diffuse conditions, both for hearing-impaired and normal-hearing listeners (Beutelmann and Brand, 2006). In Wan *et al.* (2010), an extended version of the EC model was used to explain the data sets acquired in Hawley *et al.* (2004).

HEARING-AID TECHNOLOGY AND PROCESSING

Data acquisition and measurement equipment

The experiments involved measuring hearing-instrument-related impulse responses (HRIR) on KEMAR. In this paper the HRIRs were measured on a KEMAR manikin in the horizontal plane with an angular resolution of 2 degrees. An anechoic room was used for the HRIR measurements. The room was in accordance with ISO 3745. The distance from the speaker to the rotation axis of KEMAR was 1.5 m. The speaker used in all experiments was a KEF Q85S (serial number: 740107G). The phase was inverted by connecting $(-)$ on the speaker to (+) on the ROTEL RB-1050 power amplifier. The recoded microphone signals were convolved with the inverse of the speaker impulse response before further processing. All measurements were performed at a sampling frequency of 48828 Hz using a Tucker Davis RX8 multiprocessor controlled by MATLAB R2010b, The MathWorks Inc., Natick, MA. The signal presented through the speaker was a maximum length sequence (MLS) signal (Proakis and Salehi, 1994). In the anechoic room the code length was $(2^{11}-1) = 2047$ samples. This corresponds to an acoustic distance of 14.2 m. It was found that the room reflections were below the noise floor at this distance. The corresponding intensity for the speaker signal at KEMAR's position (without KEMAR present) was 74 dB SPL. The HRIRs were measured on a pair of modified receiver-in-the-ear hearing aids where the front and the rear microphone signals were accessible.

Processing modes

Omni-mode processing was created by simply extracting the front-microphone signal from the hearing instrument. The directionality processing was created using filter and sum beamforming by placing a null at 180°. The filters in the beamformer had 21 taps. Three different hearing-aid processing configurations were tested:

- **Bilateral omni mode** was created by using the omni signal in both hearing aids.
- **Bilateral directionality mode** was created by using the beamformer output in both hearing instruments.
- **Asymmetric mode** was generated by choosing the omni signal in the right hearing instrument and the beamformer output in the left hearing instrument.

The directivity patterns for the left (black solid line) and right (gray solid line) hearing instruments can be seen in Fig. 1 (1 kHz) and Fig. 2 (4 kHz). The left plot shows the bilateral omni mode processing configuration, the middle plot shows the configuration where both hearing instruments are programmed to perform beamforming and the right plot shows the asymmetric processing configuration where one instrument performs omni-mode processing and the other performs beamforming.

SIMULATION SETUP

Four different simulations were created: 1) target at 0° and masker at 120°, 2) target at 120° and masker at 0°, 3) target at 0° and masker at $-120°$, 4) target at $-120°$ and masker at 0°. Binaural HRIRs were then created for the three different processing configurations and the resulting impulse responses were processed by the EC model. Let $A_q(f)$ be the spectrum of a realization of the target component after the EC process

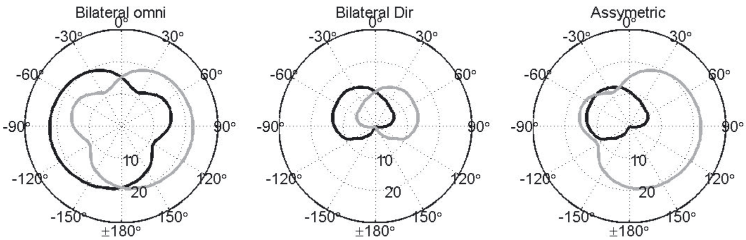

Fig. 1: Directivity patterns for the left (black solid line) and right (gray solid line) hearing instruments for the frequency of 1 kHz.

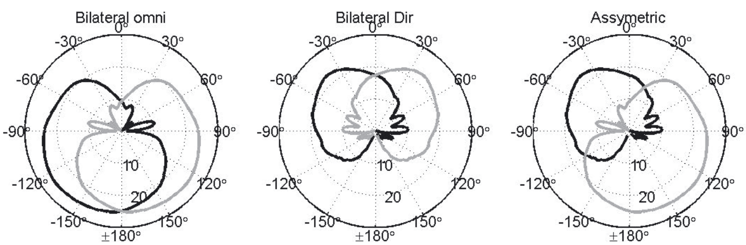

Fig. 2: Directivity patterns for the left (black solid line) and right (gray solid line) hearing instruments for the frequency of 4 kHz.

and let the corresponding masker spectrum after EC processing be given by $B_q(f)$. The binaural signal-to-noise ratio was then estimated as

$$\mathrm{SNR}(f) = \frac{\sum_{q=0}^{Q-1} \left|A_q(f)\right|^2}{\sum_{q=0}^{Q-1} \left|B_q(f)\right|^2}, \qquad \text{(Eq. 1)}$$

In this paper $Q = 10000$ realizations were used.

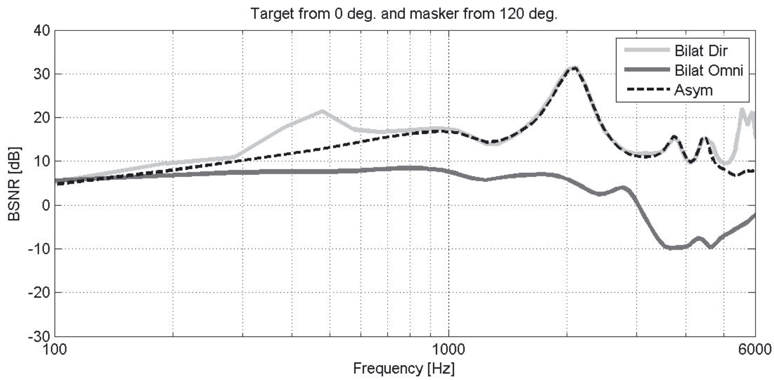

Fig. 3: Binaural SNR estimated by the EC model with a target presented from 0 degrees and a masker from 120 degrees. The bilateral omni mode is given by the dark gray curve, the bilateral directionality is given by the light gray curve, and the asymmetric configuration is seen in the dashed black plot.

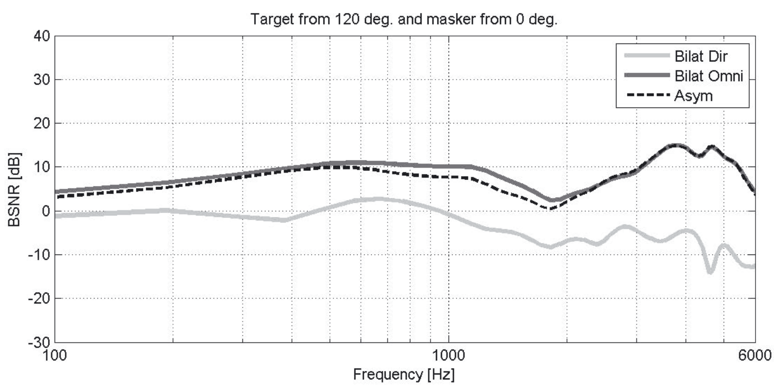

Fig. 4: Binaural SNR estimated by the EC model with a target presented from 120 degrees and a masker from 0 degrees. The bilateral omni mode is given by the dark gray curve, the bilateral directionality is given by the light gray curve and the asymmetric configuration is seen in the dashed black plot.

SIMULATION RESULTS

The binaural SNR predicted by the EC model for the four different simulations is given in Figs. 3-6. In all figures, the bilateral omni-mode results are given by the solid dark gray curve, the bilateral directionality mode results are given by the light gray curve, and the results for the asymmetric processing are given by the dashed black curve. In Fig. 3, the target and masker are configured so that the target is in front of the listener (0°) and the masker is to the side (120°). In the asymmetric processing mode, the masker faces the hearing aid which is programmed to perform omni-mode processing. The bilateral directionality mode has better SNR than the bilateral omni configuration. This is to be expected, since the directionality algorithm suppresses sources from from the rear and to the side. The asymmetric configuration, however, seems to have similar performance as the bilateral directionality mode.

In Fig. 4, the target and masker positions are interchanged compared to Fig. 3. The masker is now assumed to be positioned in the front and the target is placed to the side. For the asymmetric processing mode, the target signal is now facing the hearing aid which is programmed to perform omni-mode processing. The bilateral directionality mode has worse SNR than the bilateral omni configuration across all frequencies. Again, this is to be expected, since the has better sensitivity to the side and to the rear compared to the directionality algorithm. The asymmetric configuration, however, now seems to have similar performance as the bilateral omni mode. Comparing the results in Fig. 3 and Fig. 4, it seems as if the auditory system is able to use the processing mode which gives the best SNR for the target of interest when presented with asymmetric beampatterns.

In Fig. 5, the masker is assumed to be positioned to the left of the listener ($-120°$) and the target is in front of the listener. For the asymmetric processing mode, the masker signal is now facing the hearing aid which is programmed to perform directionality-mode processing. The bilateral directionality mode has again better SNR than the bilateral omni configuration across all frequencies. The results for the asymmetric configuration now seem to be a bit more mixed as compared to the results in Fig. 3. Up to approximately 500 Hz, the asymmetric configuration has similar SNR as the bilateral directionality mode. Above this frequency, performance seems to degrade and resembles the performance given by the bilateral omni-mode results.

In Fig. 6, the target is assumed to be positioned to the left of the listener ($-120°$) and the masker is in front of the listener. For the asymmetric processing mode, the target signal is now facing the hearing aid which is programmed to perform directionality-mode processing. The bilateral directionality mode has worse SNR than the bilateral omni configuration across all frequencies. The results for the asymmetric configuration seem to resemble the performance given by the bilateral directionality-mode results. In this target/masker setup, there seems to be no advantage of asymmetric processing. If one analyzes the beampatterns in Fig. 1 and Fig. 2, it is seen that the target position of $-120°$ is particularly unfavorable for the asymmetric configuration, as the beampatterns of both the left and the right hearing instrument display very low sensitivity in this region.

DISCUSSION

Modeling binaural listening performance with asymmetric beampatterns yields two major conclusions: If the target and masker are configured so that one of the sources is

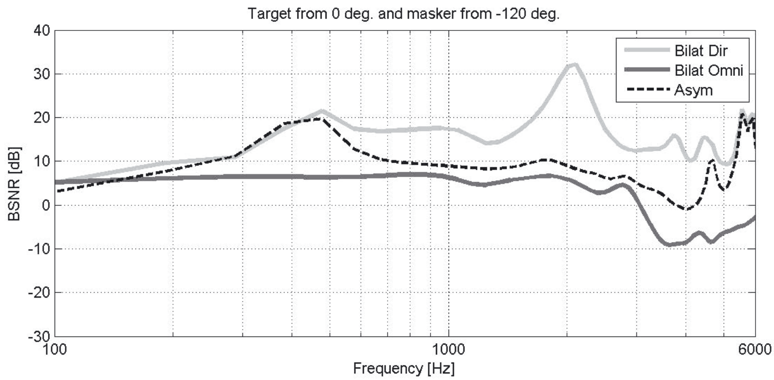

Fig. 5: Binaural SNR estimated by the EC model with a target presented from 0 degrees and a masker from 120 degrees. The bilateral omni mode is given by the dark gray curve, the bilateral directionality is given by the light gray curve and the asymmetric configuration is seen in the dashed black plot.

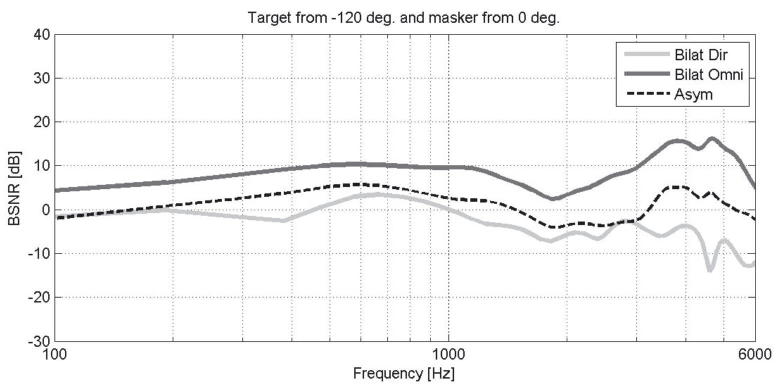

Fig. 6: Binaural SNR estimated by the EC model with a target presented from 0 degrees and a masker from 120 degrees. The bilateral omni mode is given by the dark gray curve, the bilateral directionality is given by the light gray curve and the asymmetric configuration is seen in the dashed black plot.

in front of the listener and the other source is placed facing the hearing aid performing omni-mode processing, it seems as if the listener can get the same performance as the bilateral directionality mode when listening to the source in front. However, if attention is turned to the source to the side, the listener achieves similar performance as with the bilateral omni-mode configuration. In this particular target/masker configuration, the model predicts that the asymmetric processing mode would yield good speech understanding to the front as well as to the side. When one source is placed in the front and the other source is placed facing the hearing instrument programmed for directionality, the results are more mixed. When trying to focus on the source in front, a listening benefit is seen up to approximately 500 Hz. When trying to focus on the source to the side the asymmetric processing only displays small improvement as compare to the bilateral directionality configuration. This suggests that if this listening situation occurs, the hearing-aid system should switch so that the hearing aid facing the interferer performs omni-mode processing.

REFERENCES

Bentler, R.A., Egge, J.L., Tubbs, J.L., and Dittberner, A.B. (**2004**). "Quantification of directional benefit across different polar response patterns," J. Am. Acad. Audiol., **15**, 649-659.

Beutelmann, R., and Brand, T. (**2006**). "Prediction of speech intelligibility in spatial noise and reverberation for normal-hearing and hearing impaired listeners," J. Acoust. Soc. Am., **120**, 331-342.

Cord, M., Surr, R., Walden, B., and Dittberner, A.B. (**2005**). "Asymmetric directional microphone fittings," American Academy of Audiology 17th Annual Convention, Washington D.C.

Culling, J.F., Hawley, M.L., and Litovsky, R.Y. (**2004**). "The role of head induced interaural time and level differences in the speech reception threshold for multiple interferring sound sources," J. Acoust. Soc. Am., **116**, 1057-1065.

Durlach, N.I. (**1960**). "Note on the equalization and cancellation theory of binaural masking level differences," J. Acoust. Soc. Am., **32**, 1075-1076.

Durlach, N.I. (**1963**). "Equalization and cancellation theory of binaural masking level differences," J. Acoust. Soc. Am., **35**, 1206-1218.

Hawley, M.L., Litovsky, R.Y., and Culling, J.F. (**2004**). "The benfit of binaural hearing in a cocktail party: Effect of location and type of interferer," J. Acoust. Soc. Am., **115**, 833-843.

Hornsby, B.W.Y., and Ricketts, T.A. (**2007**). "Effects of noise source configuration on directional benefit using symmetric and asymmetric directional hearing aid fittings," Ear Hearing, **28**, 177-186.

Kock, W.E. (**1950**). "Binaural localization and masking," J. Acoust. Soc. Am., **22**, 801-804.

Proakis, J.G., and Salehi, M. (**1994**). *Communcation Systems Engineering* (Prentice Hall).

Ricketts, T., and Dittberner, A.B. (**2002**). "Directionality amplification for improved signal-to-noise ratio: Strategies, measurements and limitations," in *Hearing Aids: Standards, Options and Limitations*, 2nd ed. Edited by M. Valente, pp. 274-346.

Wan, R.W., Durlach, N.I., and Colburn, H.S. (**2010**). "Application of an extended equalization-cancellation model to speech intelligibility with spatially distributed maskers," J. Acoust. Soc. Am., **128**, 3678-3690.

Zurek, P.M. (**1992**). "Binaural advantages and directional effects in speech intelligibility," in *Acoustical Factors affecting Hearing Aid Performance*, 2nd ed. Edited by G.A. Studebaker and I. Hochberg (Allyn and Bacon, Boston), pp. 255-276.