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Le Goff, Nicolas; Kohlrausch, Armin

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THE EFFECT OF COCHLEAR NONLINEARITIES ON BINAURAL MASKING LEVEL DIFFERENCES

Nicolas Le Goff[1] and Armin Kohlrausch[2,3]

1. Technical University of Denmark, 2. Philips Research Europe, 3. Eindhoven University of Technology

Contact: nlg@elektro.dtu.dk, armin.kohlrausch@philips.com

Introduction

The detection of a tone in noise is improved when the interaural phase difference of the signal at the two ears is not the same as that of the masker. The detection threshold of a tone presented with a 180-degree interaural phase difference in a diotic noise masker is typically lower than the detection threshold of a tone in a masker, both presented at one ear only. This difference between monaural and binaural detection thresholds is commonly referred to as the *binaural masking level difference* (BMLD) and can be as large as 15 dB for broadband noise.

It is known that the BMLD decreases with lower masker levels. As shown in Fig.1 the decrease is larger when the masker is attenuated in one ear only (red square) than when it is attenuated at the two ears (green diamonds). *The present study investigates whether cochlear nonlinearities are sufficient to explain this difference in reduction of the BMLD for lower masker levels in one or two ears.*

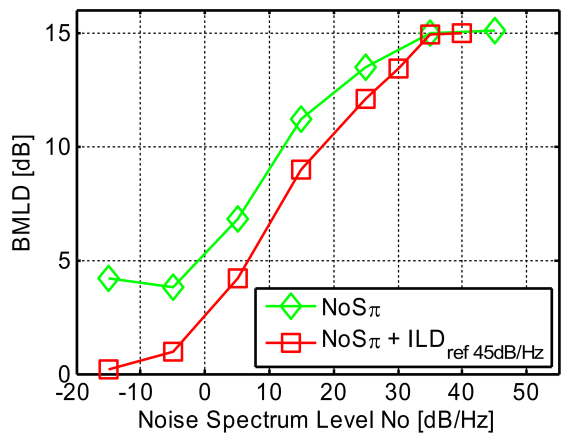


Fig 1: BMLD as a function of noise spectrum level with noise attenuated in two ears (diamond) or in one ear (square). Data replotted from McFadden (1968)

In this study, the BMLD was measured for 500-Hz tones in 3-kHz-wide maskers with a level between -10 and 50 dB/Hz. As in McFadden (1968) the masker was attenuated in either one or two ears. For attenuation in one ear only, thresholds were measured for two masker levels in the non-attenuated ear (reference level) of either 20 or 50 dB/Hz.

Hypothesis:

The response of the cochlea is level-dependent and nonlinear. Cochlear nonlinearities could therefore cause a reduction in interaural correlation between the left and right internal representations of the noise masker presented at different levels in the two ears, which *in effect* would reduce the efficiency of the detection process.

Two binaural model implementations were considered to test this hypothesis: (i) The equalization-cancellation (EC) binaural model proposed by Breebaart et al. (2001), which includes a linear gammatone filterbank; (ii) an extension of the model proposed by Breebaart et al. (2001) with nonlinear peripheral processing (Jepsen et al., 2008) that includes a dual resonance nonlinear filterbank peripheral (DRNL, Lopez-Poveda and Meddis, 2001);
Model predictions obtained with the two models were compared to test whether the nonlinear cochlear processing in the DRNL filterbank is necessary and sufficient to account for the effect of interaural masker level differences on the BMLD. Model predictions obtained with the extended nonlinear model are consistent with the experimental data.

Research Question:

Are the nonlinearities in the cochlea necessary and sufficient to explain the effect of interaural masker level differences on tone-in-noise detection?

Research Tools:

An equalization cancellation (EC) binaural model that includes either a gammatone or a dual-resonance nonlinear (DRNL) filterbank and a nonlinear adaptation stage.

Model

Two model implementations were considered. Both were signal driven bottom-up processors used as artificial observer. Both implementations assume two sources of internal noise: one to limit audibility (5dB SPL@500Hz), in the peripheral processor, and one to limit the binaural accuracy. The two model implementations only differed in the filterbank properties.

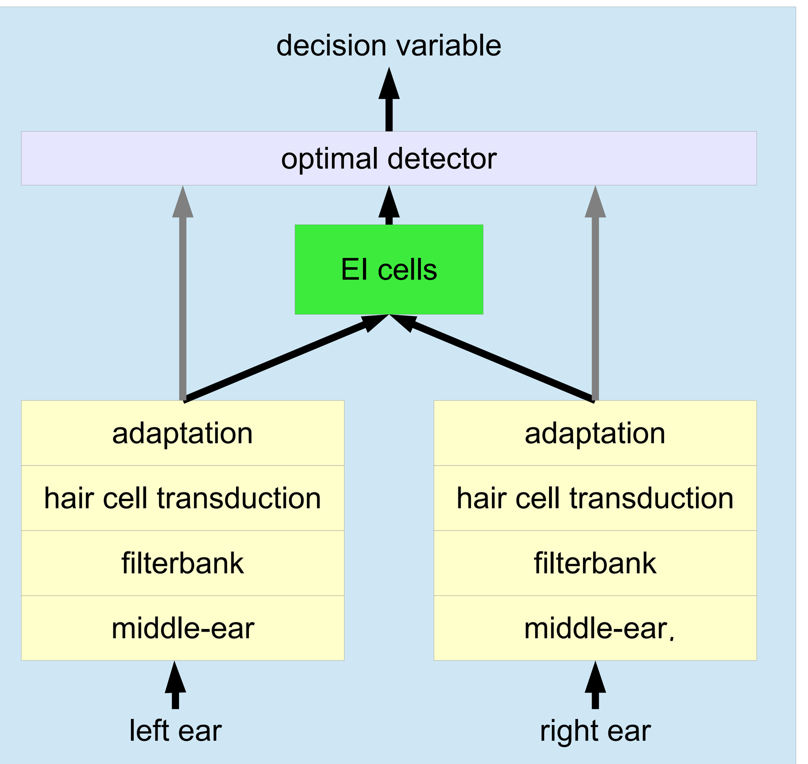


Fig 2: Block diagram of the models. The left- and right-ear input signals are processed in the peripheral processor and compared in the EC-type binaural processor. The central processor is an optimal detector. A gammatone filterbank is used in the Breebaart et al. (2001) model and a DRNL filterbank is used in the proposed nonlinear model.

Central processor:
- Detector that optimally integrates information in time and frequency (Breebaart et al., 2001)

Binaural processor:
- Equalization-cancellation (EC) processor consisting of excitation-inhibition (EI) cells (Breebaart et al., 2001)

Peripheral processor:
- Adaptation stage that accounts for forward masking(1).
- Halfway rectifier and 1-kHz lowpass filter to account for hair cell transduction
- Filterbank:
  - Gammatone in the Breebaart et al. (2001) model.
  - Dual resonance non linear (DRNL) filterbank (Lopez-Poveda and Meddis 2001) in the extended model.
- Bandpass filter to account for middle-ear filtering

DRNL filterbank:

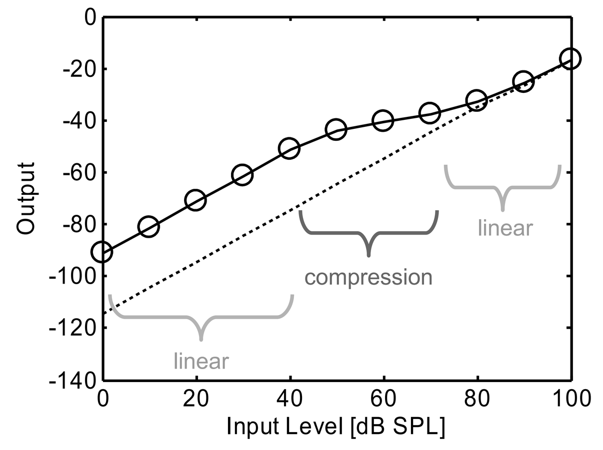


Fig 3: Input/ouput function of the filterbank at 500Hz. The response of the DRNL filterbank is shown by the circles. The dotted line represents a linear response, as obtained with a gammatone filterbank

The nonlinear cochlear response is modeled by the DRNL filterbank. It is characterized by:
- Level-dependent auditory filter bandwidths.
- Nonlinear input-ouput function.

The response of the DRNL in the present model was fitted to temporal masking curve data (Jepsen et al., 2011). The input/output response has three distinct phases:
- Linear response for input levels < 50 dB SPL
- Compressive response with a ratio of 0.25 for input levels between 50 and 80 dB SPL
- Linear response for input levels > 80 dB SPL

The auditory filter bandwidths of the DRNL filterbank are similar to those of 4th order gammatone filters at low levels and increase for higher input levels.

(1): Here the adaptation stage has been modified with a limitation of the onset overshoot (Jepsen et al. 2008) as compared to the original model implementation.

Experiment: Tone-in-noise detection as a function of the masker level

Detection of a 500-Hz tone (200 ms) in a 3-kHz-wide noise masker (300 ms) - 3 subjects - 3 repetitions per subject - 3-AFC adaptive adjustment of the level of the tone

NmSm:
- Monaural masker
- Monaural tone

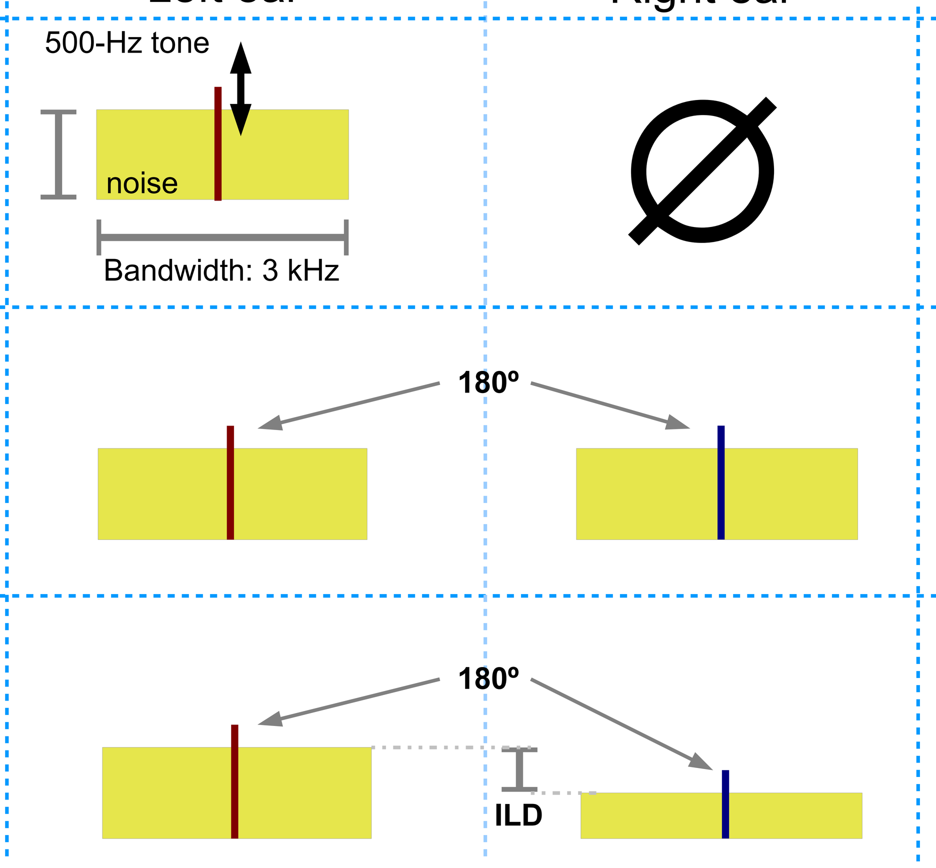
Levels: -10N-∞, 0N-∞, 10N-∞, 20N-∞, 30N-∞, 40N-∞, 50N-∞ (noise spectrum level in the left ear [dB/Hz] / noise spectrum level in the right ear [dB/Hz])

NoSπ:
- Diotic masker
- Tone with 180° interaural phase difference

Levels: -10N-10, 0N0, 10N10, 20N20, 30N30, 40N40, 50N50

No'Sπ':
- NoSπ + ILD applied on **tone and masker**
- Level in non-attenuated ear: 50 or 20 dB/Hz

No'Sπ'50	No'Sπ'20	ILD [dB]
-10N50		60
0N50		50
10N50		40
20N50	-10N20	30
30N50	0N20	20
40N50	10N20	10



Results

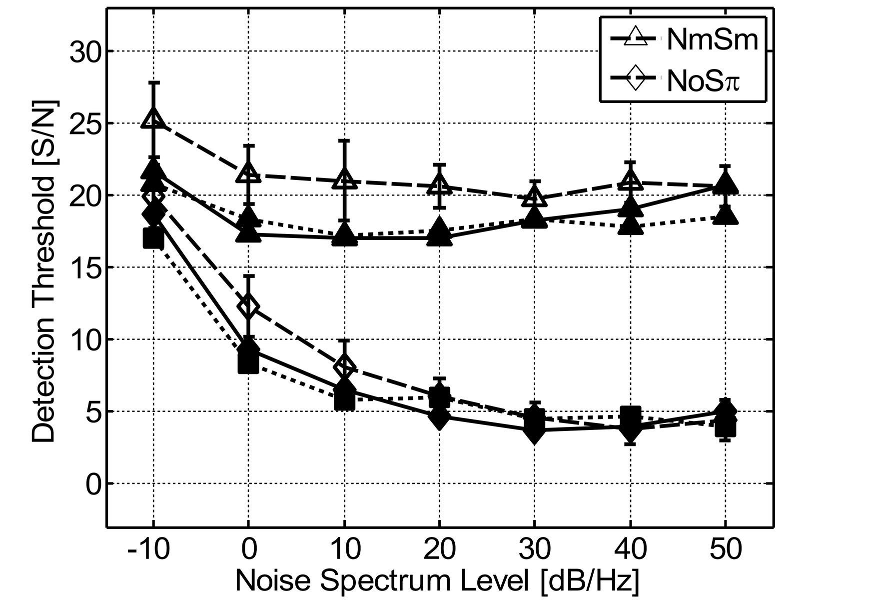


Fig 5: NmSm and NoSπ detection thresholds as a function of the masker level. Experimental data are represented by open symbols and model data by filled symbols. Model predictions obtained with the Breebaart et al. (2001) model are shown by dotted lines and predictions obtained with the extended nonlinear model are shown by the continuous lines.

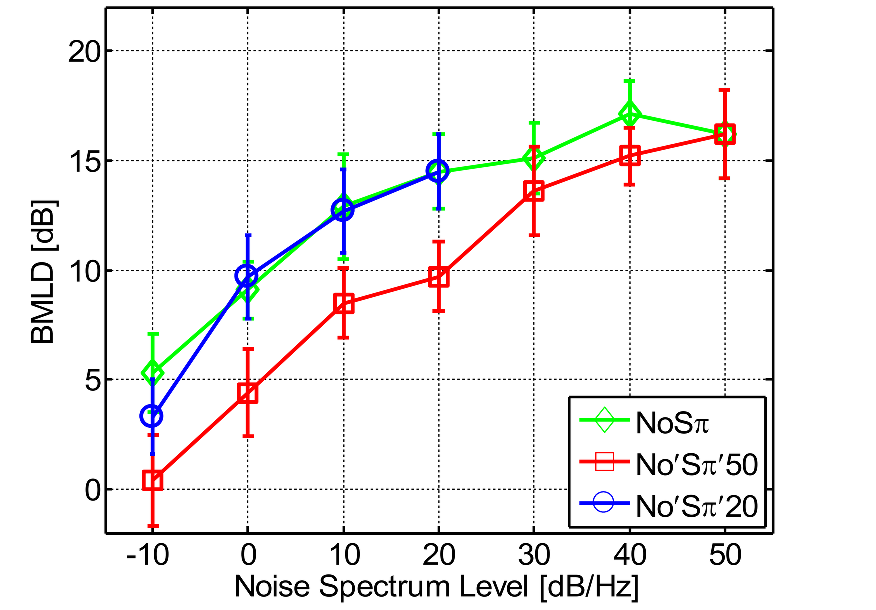


Fig 6: BMLD for NoSπ and for No'Sπ' as a function of the noise spectrum level. For the NoSπ function, the abscissa designates the noise spectrum level in both ears. For the No'Sπ' functions, the abscissa designates the spectrum level in the ear with the less intense noise; the other ear received a spectrum level of either 50 dB (red square) or 20 dB (blue circles). The reference condition for the NoSπ conditions was the corresponding NmSm condition. The reference stimulus of the No'Sπ'50 conditions was 50N-∞. The reference stimulus of the No'Sπ'20 conditions was 20N-∞.

In line with literature data (e.g., Bernstein & Trahiotis, 2008):
- NmSm: constant for No > 0 dB/Hz (external noise); increase for lower levels (internal noise).
- NoSπ: constant for No > 30 dB/Hz (external noise); increase for lower levels (internal noise).
- Both the Breebaart et al. (2001) model and the extended nonlinear model account well for the data.

In line with literature data (McFadden, 1968):
- BMLD for No'Sπ'50 (red) is lower than BMLD for NoSπ (green) at corresponding masker levels.

New:
- BMLD for No'Sπ'20 (blue) is equal to the BMLD for NoSπ (green) at corresponding masker levels.

Model Predictions

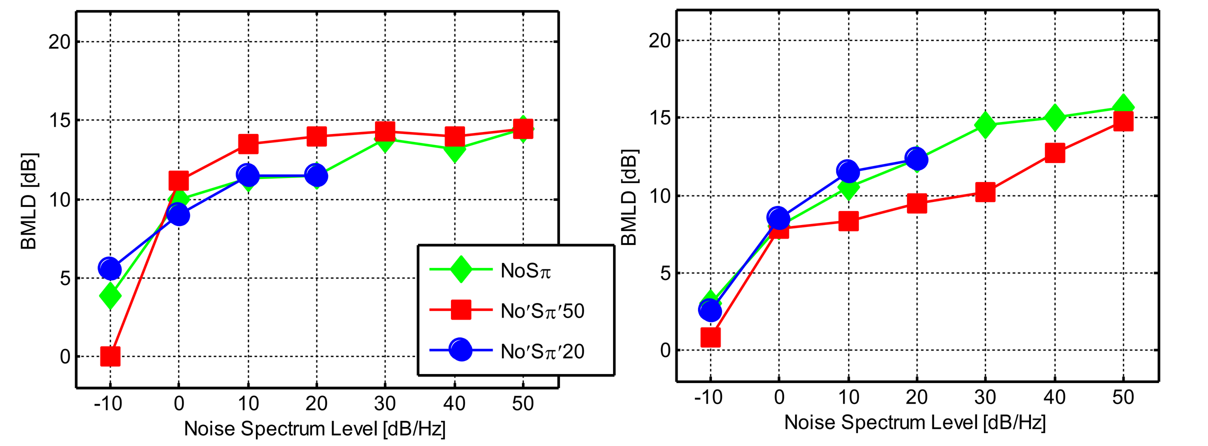


Fig 7: Simulation of the BMLD for the three binaural conditions. Predictions obtained with the Breebaart et al. (2001) model (gammatone filterbank) are shown in the *left* panel. Predictions obtained with the extended *nonlinear* model (DRNL filterbank) are shown in the *right* panel.

- In line with predictions for NoSπ and NmSm in Fig. 5, the BMLD for NoSπ as a function of the masker level is correctly predicted by both models.
- The BMLDs as a function of the masker level for No'Sπ'50 and No'Sπ'20 are predicted by the extended nonlinear model, while the Breebaart et al (2001) model can only predict the BMLD for the No'Sπ'20 condition.

Discussion

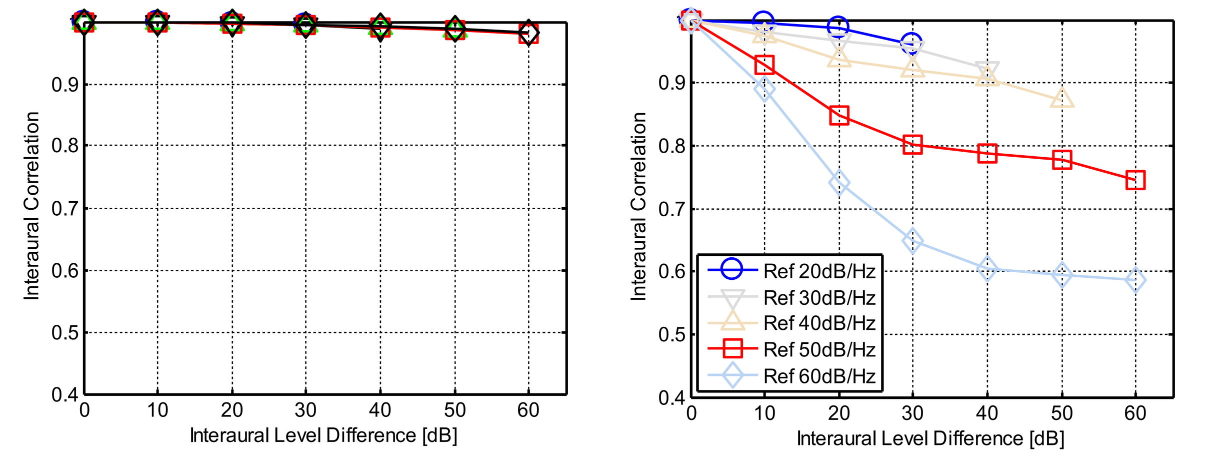


Fig 8: Interaural correlation measured at the output of the peripheral processor for masker signals as a function of the ILD. Results are shown for five reference levels in the non attenuated ear. Predictions obtained the Breebaart et al. (2001) model (gammatone filterbank) are shown in the *left* panel. Predictions obtained with the extended *nonlinear* model (DRNL filterbank) are shown in the *right* panel.

Linear peripheral processor:
- Interaural correlation (IC) is -almost- constant and equal to one. Small decrease due to the adaptation stage.

Nonlinear peripheral processor:
- IC decreases rapidly for ILD up to 30 dB, remains nearly constant for larger ILDs.
- Decrease in IC is stronger for higher reference levels (No).

(nonlinear) Model Analysis	Experimental Data
Ref level 20dB/Hz & 0<ILD<30dB Ref level 50dB/Hz & 30<ILD<60dB ⇒no or small change in IC with ILD	BMLD for No'Sπ'20 follows BMLD for NoSπ, BMLDs for No'Sπ'50 and NoSπ decrease in parallel for No<20dB/Hz
Ref level 50dB/Hz & 0<ILD<30dB ⇒decrease in IC with ILD	BMLD for No'Sπ'50 decreases *more* than BMLD NoSπ for 20<No<50dB/Hz

Effect of ILD on BMLD is accounted for by cochlear nonlinearities, which can cause a decrease in IC in the internal representations of the masker depending on the reference level of the masker.

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