A Subcortical Auditory Model With Efferent Gain Control Explains Perceptual Enhancement

Afagh Farhadi, Swapna Agarwalla, Laurel H. Carney

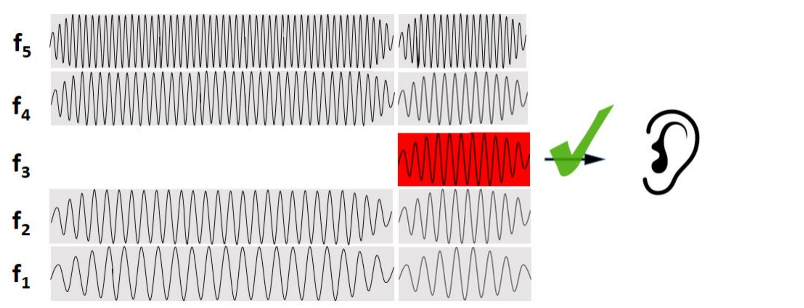
Departments of Electrical & Computer, Biomedical Engineering, and Neuroscience, University of Rochester, New York, USA

University of Rochester

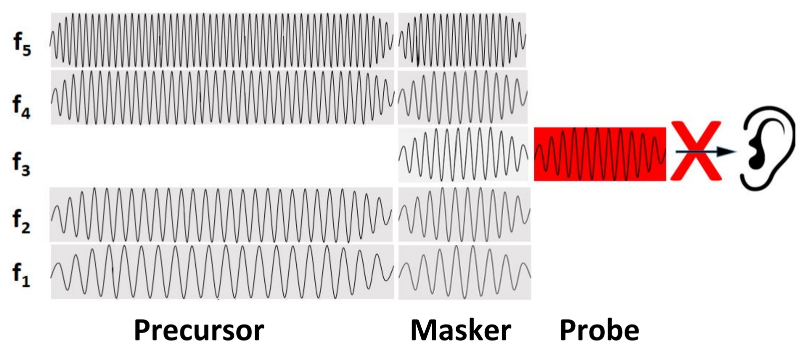
Hearing & Balance Research Collective

Introduction

Auditory Enhancement : A target embedded in a background sound "pops out" when it follows a precursor consisting of the background alone (Viemeister, 1980).



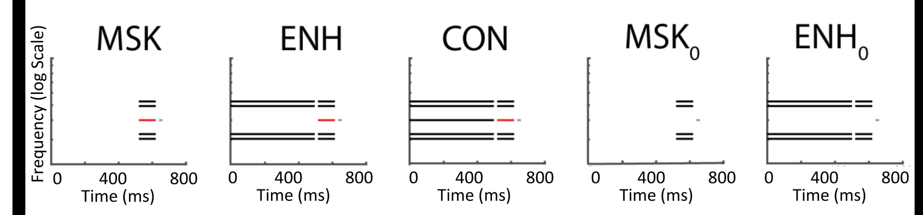
Masker Enhancement : The enhanced target is a more effective forward masker of a delayed probe tone (Viemeister & Bacon, 1982).



The focus of this study was predicting masker enhancement for listeners with normal (NH) and impaired (HI) hearing, as reported in Kreft & Oxenham (2019). They showed surprising effects of SPL and HI on the amount of enhancement.

We tested the hypothesis that a subcortical model including the dynamics of the efferent system (Farhadi et al., 2022) could explain masker enhancement.

Methods



Five stimulus conditions were simulated (Kreft & Oxenham, 2019). Signal frequency was 4 kHz. Maskers and precursors included components at 2462.3, 2639.0, 6062.9, 6498.0 Hz.

In all conditions, a 20-ms, 4-kHz probe tone followed:

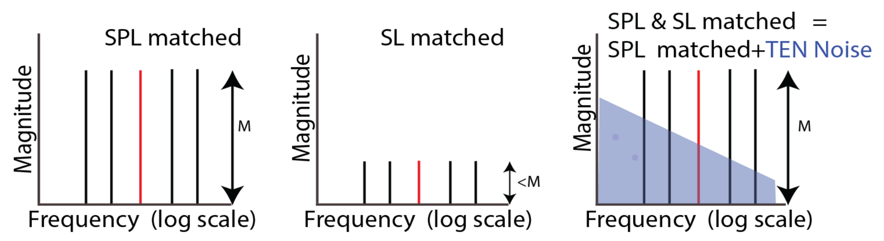
MSK = Masker that included signal frequency (Baseline)

ENH= Added precursor without signal frequency (Enhanced condition)

CON = Control; Precursor contained signal freq (No Enhancement)

MSK_0 = Masker without signal frequency

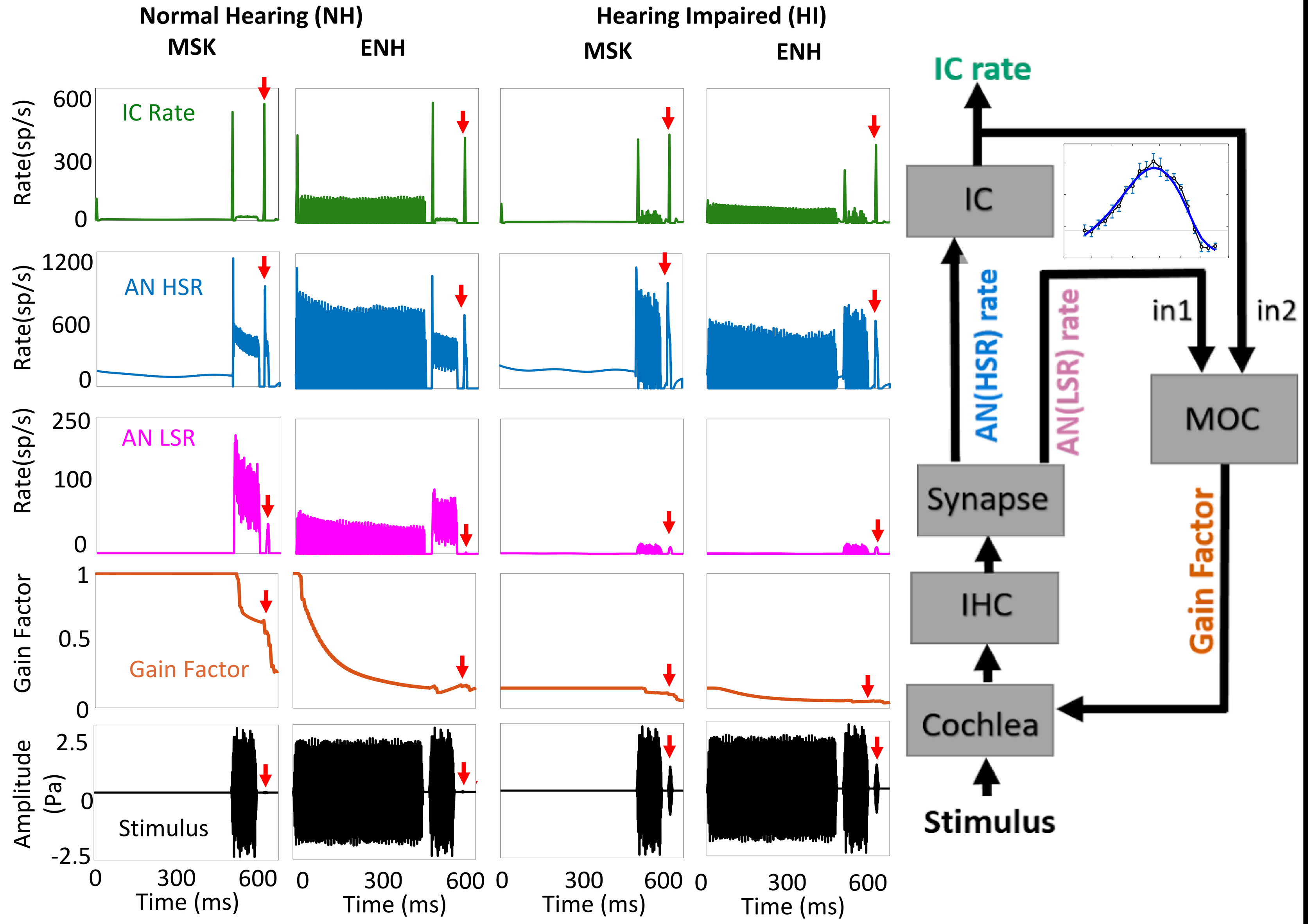
ENH_0 = Precursor and masker both lack signal frequency. The latter two conditions controlled for effect of masker/precursor duration.



Probe level was varied to estimate detection threshold for NH and HI models. NH thresholds were estimated for 3 level configurations: (1) SPL matched to that used for HI (85 dB SPL/comp), (2) sensation level (SL) matched to average HI SL, and (3) SPL = 85 dB SPL & SL matched to average HI listener using threshold equalizing noise (TEN) (Kreft & Oxenham, 2019). Masker level for same-SL and noise level for same SPL & SL condition were adjusted based on model thresholds.

Model Response

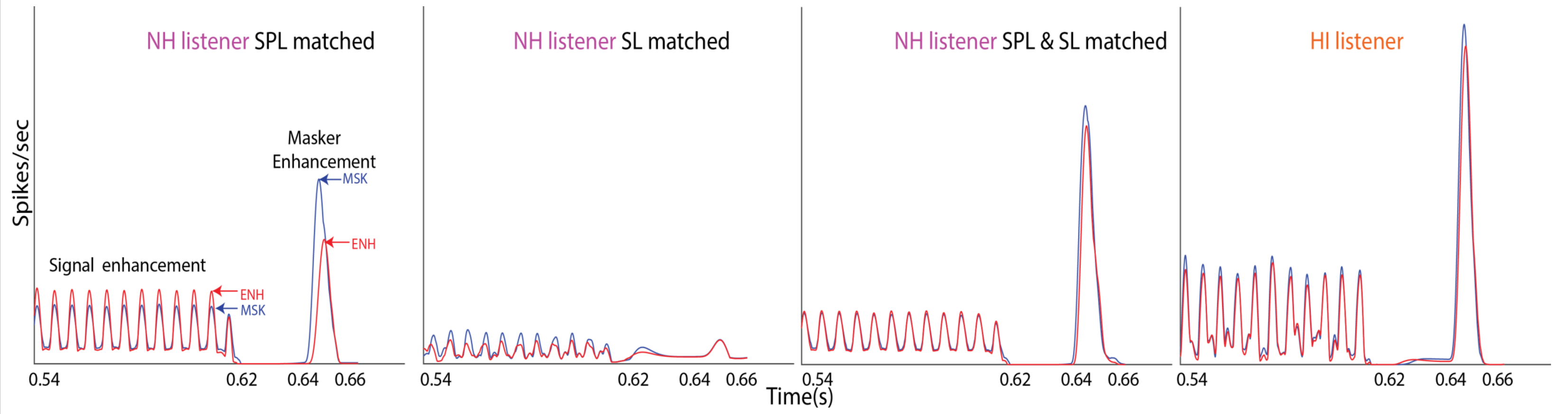
In all of the simulations illustrated, the probe level was approximately 3 dB above the model threshold for the ENH condition (60 dB SPL for NH; 90 dB SPL for HI.)



Subcortical model: MOC efferents receive inputs from wide-dynamic-range brainstem cells (modeled by low-spontaneous-rate AN fibers) and from the midbrain neurons excited by fluctuations (Farhadi et al., 2022). The MOC combines the feedback signals and adjusts cochlear gain. Responses of model stages, for CF=4-kHz, are shown in response to a masker alone (MSK) and masker with precursor (ENH), for NH and HI, to illustrate the mechanism for auditory enhancement. The probe level was set above threshold for both HI and NH models. For NH, the precursor reduced the cochlear gain, resulting in what appears to be more effective masking by the target in ENH (red arrows). For HI, the already reduced cochlear gain was little effected by the precursor, resulting in less enhancement.

Decision Variable

Model thresholds for probe detection were estimated using the method of constant stimuli. Probe level was varied. A logistic fit to % correct vs. level identified 70.7%-correct threshold. For each two-interval trial, the decision variable was the rate, summed over 9 IC BE cells with CFs spanning the masker components. Rate was summed over a 105-ms time window that included the final 25 ms of the masker and the entire probe tone.

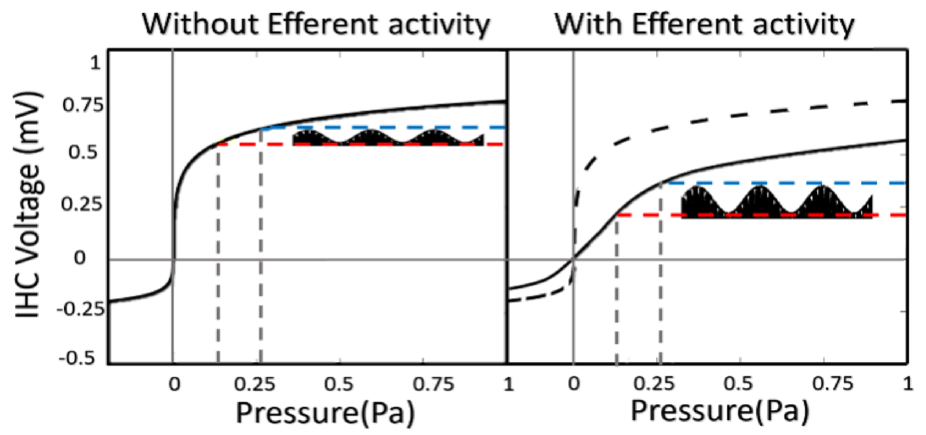


NH SPL-matched condition (Left): the stronger summed IC BE response during the masker for the ENH condition (red) is consistent with target enhancement ("pop out"). The reduction in the response to the probe is consistent with masker enhancement. Smaller differences in other conditions, and for HI, are consistent with the reduced enhancement observed experimentally (Kreft & Oxenham, 2019).

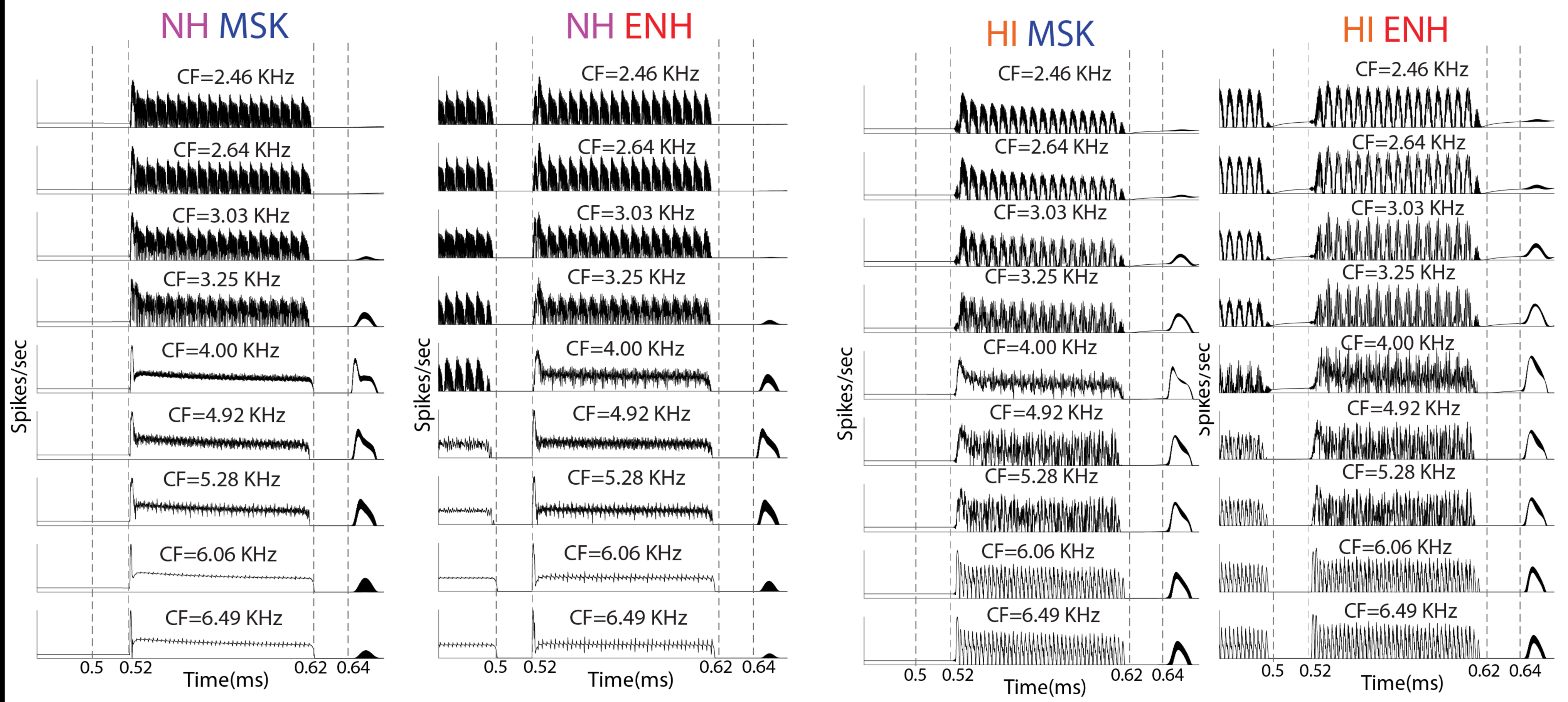
Hypothesis

Proposed Mechanism for Perceptual Enhancement

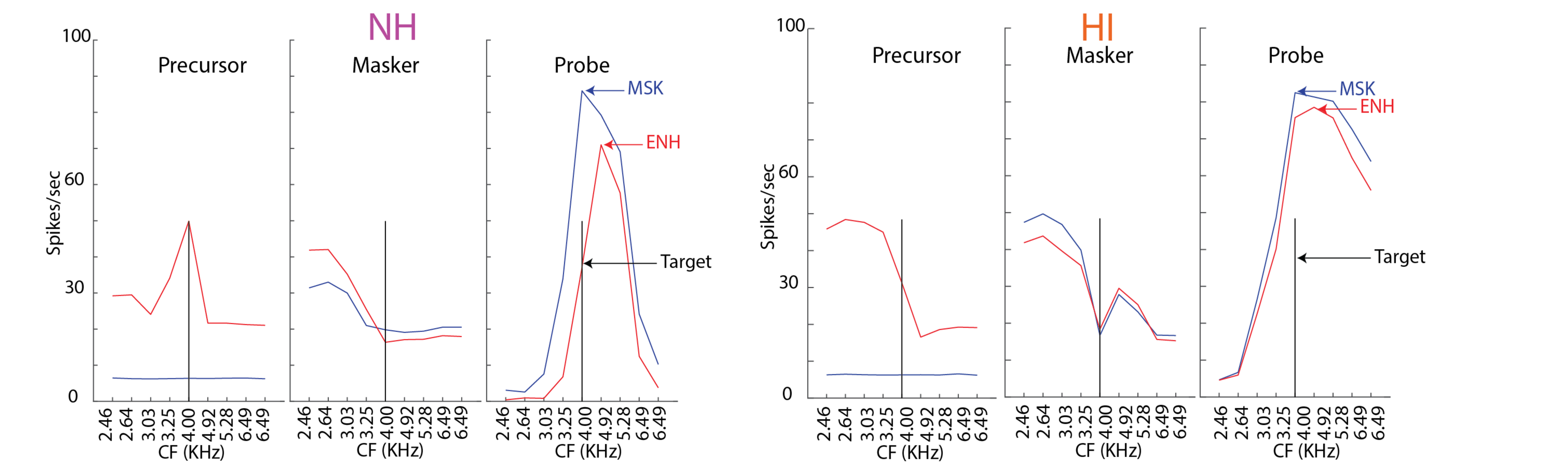
Saturation of IHCs affects depth of fluctuations of auditory-nerve (AN) and IC responses in response to precursor. Efferent activity driven by IC BE neurons that are excited by fluctuations reduces cochlear gain, further increasing low-frequency fluctuations in AN response (shown at right), and further increasing IC BE responses during MSK and probe responses occur for the HI model, for which cochlear gain is already reduced.



PSTHs of AN HSR Responses for 9 CFs spanning masker/precursor



Rate profiles across CF, for IC BE responses during each epoch of stimulus (precursor, masker, probe tone):



High-spontaneous-rate (HSR) AN (top) and IC BE responses (bottom) for the 9 CF channels spanning the masker/precursor component frequencies.

Masker Responses: AN HSR responses (top) to the masker have strong fluctuations for low-CFs, where multiple component frequencies fall within AN tuning curves. These AN HSR fluctuations result in stronger IC BE masker response rates (bottom) at low CFs, which would improve detection of the target (**Auditory enhancement**).

Precursor Responses: Fluctuations in the AN HSR responses (top) to the precursor are especially strong at 4 kHz, due to the lack of the target component. These fluctuations drive IC BE responses at 4 kHz (bottom) resulting in efferent gain reduction over the time course of the precursor in the ENH condition.

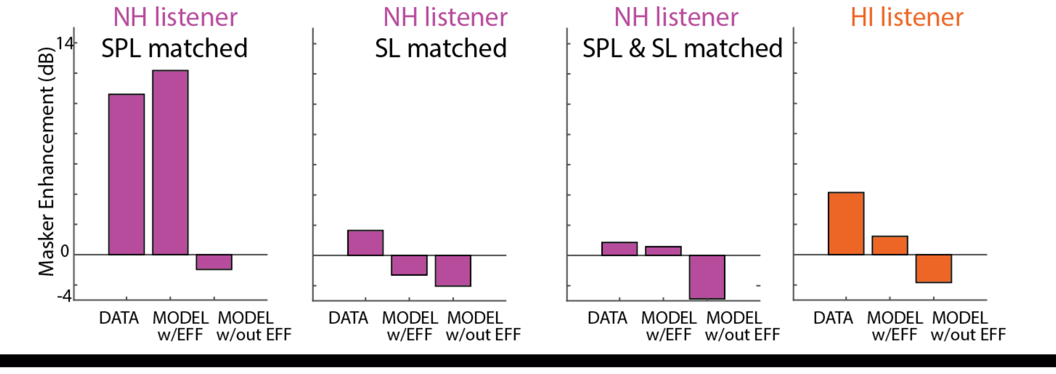
Probe Responses: Reduction of cochlear gain during over the time course of the precursor reduces IC BE response to the probe in the ENH condition (bottom), impacting forward-masked thresholds (**Masker Enhancement**). The difference in IC BE rates to the probe, summed across all CFs, is larger for NH than for HI, explaining the greater Masker Enhancement for NH compared to HI.

Results

Thresholds of the model with MOC efferents exhibited the following key trends observed in the psychoacoustic data:

- The NH model had significant enhancement in the SPL-matched condition (top row), but no enhancement when SL, or both SPL & SL, were matched to those for HI listeners.
- The model with hearing loss had no enhancement (orange symbols).
- A model without efferent gain control failed to capture these effects.
- The largest discrepancies between model and data are absolute thresholds in the NH SPL & SL matched condition.

Amount of enhancement for each condition is illustrated in the bar plot below. The key result is the successful prediction of enhancement for the NH SPL matched condition, for the model with efferent gain control, with little enhancement in all other conditions, as observed in psychophysical data.



Conclusions and Future Work

A subcortical model with MOC efferents simulated masker enhancement observed in NH and HI listeners in three sound-level conditions, whereas a model without efferents failed to do so.

These findings support the hypothesis that efferent activity could explain auditory enhancement.

Farhadi A, Jennings SG, Strickland EA, Carney LH. (2022) Auditory-nerve Model including Efferent Dynamic Gain Control with Inputs from Cochlear Nucleus and Inferior Colliculus. bioRxiv 2022.10.25.513794 [**Preprint**].

Kreft, H. A., & Oxenham, A. J. (2019). Auditory enhancement under forward masking in normal-hearing and hearing-impaired listeners. *JASA*, *146:* 3448-3456.

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