Simulating Masking and Anti-masking Effects of Medial Olivocochlear Efferent Reflex

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Overview

Introduction

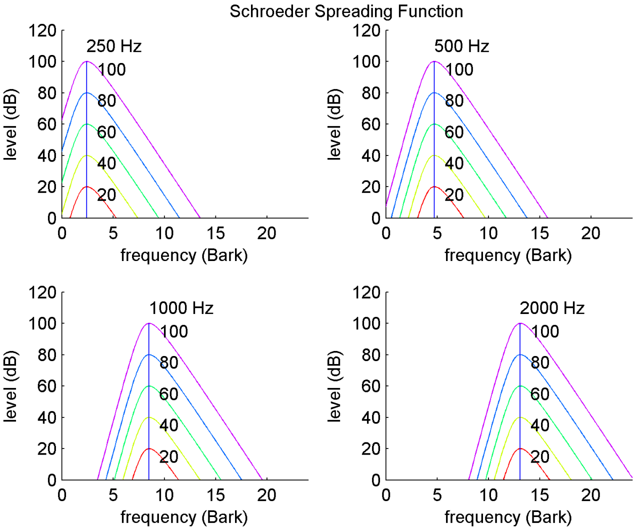
Motivation

- Studying the physiological basis of psychoacoustical phenomena is difficult.
- Combining of existing physical models of hearing organs to simulate psychophysical phenomena - auditory masking and anti-masking.

Auditory Masking & Anti-masking

- Masking:
  Masking effects occur when perception of a target sound is affected by presence of other sounds.
  - ex: Talking on the street.
- Anti-masking:
  Anti-masking effects unmask the target sound when in a noisy background.
  - ex: Chatting in a night market.

Masking Curves



Research about Anti-masking

- Kawase et al. have recorded the auditory nerve (AN) spiking rate of medial olivocochlear reflex (MOCR)[1].
- Chintanpalli et al. used filtering techniques to reduce the OHC gain and simulated open-loop anti-masking simulation[2].
- Housley and Ashmore's experiment showed that acetylcholine (ACh) made the OHC conductance to increase[3].

[1] T. Kawase, B. Delgutte, and M. C. Liberman, "Antimasking effects of the olivocochlear reflex. II. enhancement of auditory-nerve response to masked tones.," *Journal of neurophysiology*, vol. 70, no. 6, pp. 2533–2549, Dec. 1, 1993.

[2] A. Chintanpalli, S. G. Jennings, M. G. Heinz, *et al.*, "Modeling the anti-masking effects of the olivocochlear reflex in auditory nerve responses to tones in sustained noise.," *Journal of the Association for Research in Otolaryngology : JARO*, vol. 13, no. 2, pp. 219–235, Apr. 2012.

[3] G. D. Housley and J. F. Ashmore, "Direct measurement of the action of acetylcholine on isolated outer hair cells of the guinea pig cochlea," *Proceedings: Biological Sciences*, vol. 244, no. 1310, pp. 161–167, May 22, 1991.

Main Contribution of this Work

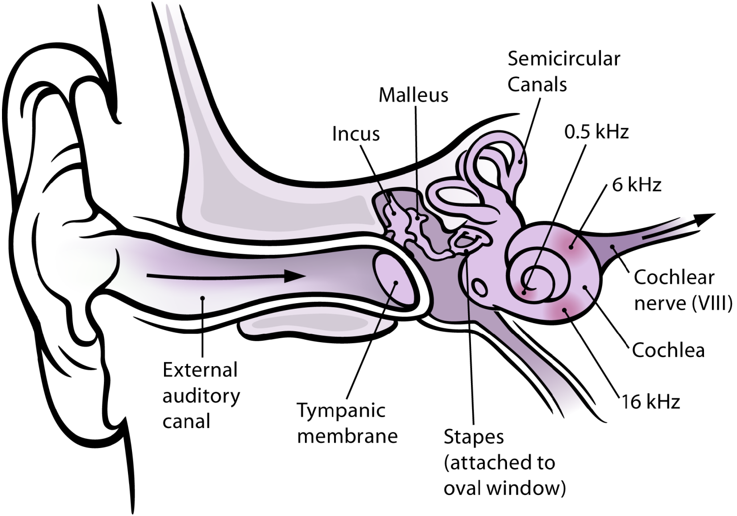
- Simulating the masking effects by designing stimulus inputs.
- Simulating the anti-masking effects by including the medial olivocochlear (MOC) reflex model.
  - The MOC increases the outer hair cells (OHCs) conductance, and reduces the gain when receiving noise inputs.
- Including a inhibitory model, tuberculoventral (TUB) cell to compare the changes in anti-masking effect.
  - The TUB cells inhibits the T-multipolar (TM) cells to reduce the anti-masking effects.
  - The TUB cells inhibits the neighbor TUB cells, and causes lateral inhibition.

The Auditory System

The Auditory System

- Peripheral auditory system
  - It starts with the ear and ends with auditory nerves.
  - It converts acoustic pressure waves into neural action potentials.
- Central auditory system
  - It starts with auditory brainstem and ends with auditory cortex.
  - It carrys neural information to the brain.

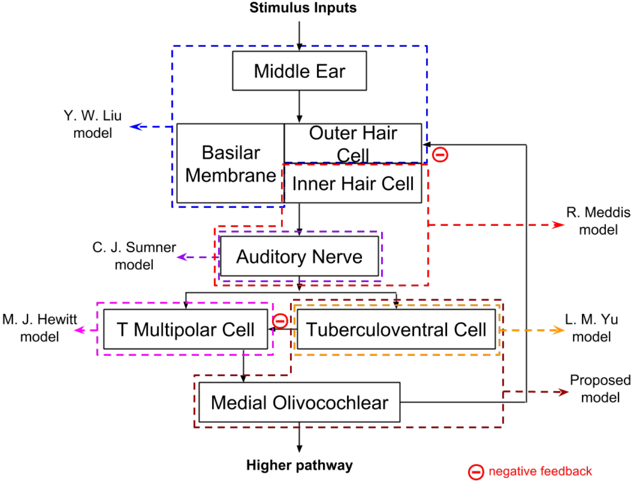
Peripheral Auditory System



[4]

[4] Chittka and Brockmann, "Perception Space - The Final Frontier" , vol. 3, e137+, Apr. 2005.

Model Structure



Reference Models

- OHC & cochlea model - Liu and Neely model[5]
  - cochlear mechanism
  - OHC mechanoeletrical transduction
  - OHC electromotility
- IHC model - Sumner et al. model[6]
  - IHC receptor potential
  - calcium controlled transmitter release function
  - quantal and probabilistic model of synaptic adaptation
- TM - Hewitt et al. model[7]
  - Dendrite
  - Soma

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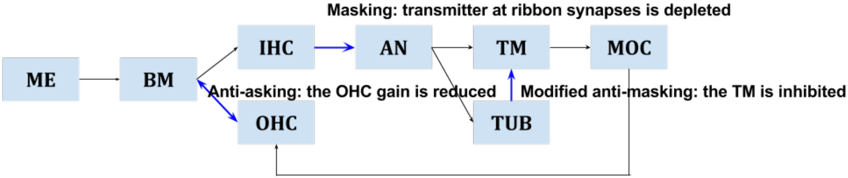
[5] Liu and Neely, "Distortion product emissions from a cochlear model with nonlinear mechanoelectrical transduction in outer hair cells." , vol. 127, pp. 2420–2432, Apr. 2010.

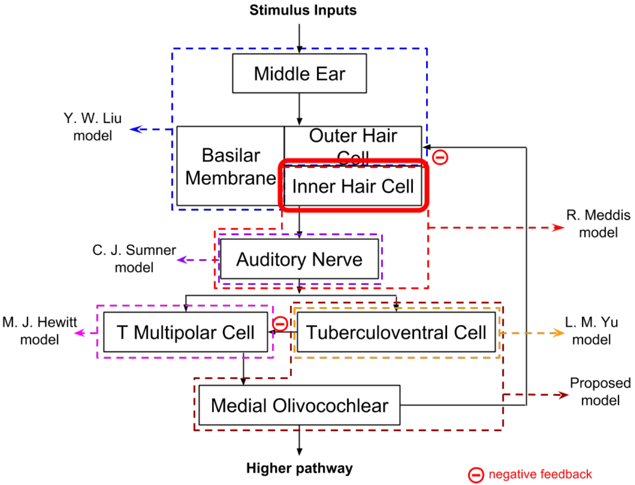
[6] Sumner, Lopez-Poveda, O'Mard, *et al.*, "A revised model of the inner-hair cell and auditory-nerve complex." , vol. 111, pp. 2178–2188, May 2002.

[7] Hewitt, Meddis, and Shackleton, "A computer model of a cochlear-nucleus stellate cell: responses to amplitude-modulated and pure-tone stimuli." , vol. 91, pp. 2096–2109, Apr. 1992.

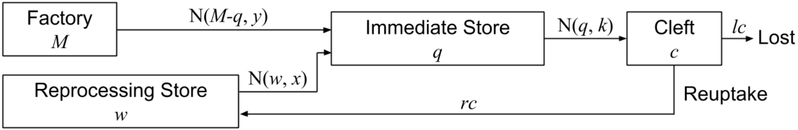
Masking & Anti-masking Mechanism



The IHC Model



Sumner et al. Model - Quantal and Probabilistic Model of Synaptic Adaptation

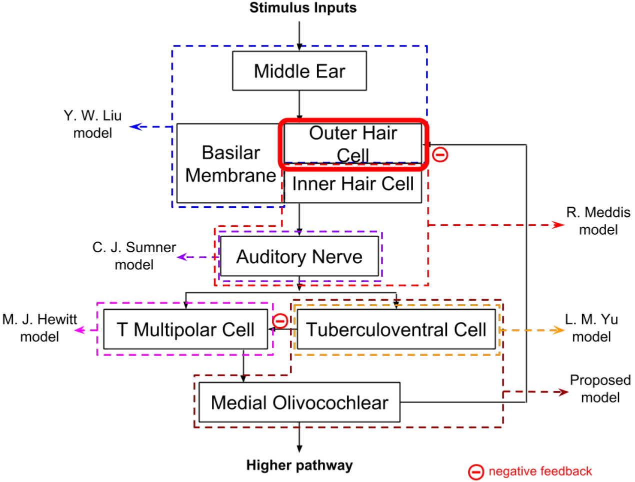


$$q(n+1) - q(n) = N(w(n), x) + N([M - q(n)], y) - N(q(n), k(n)) \quad (1)$$

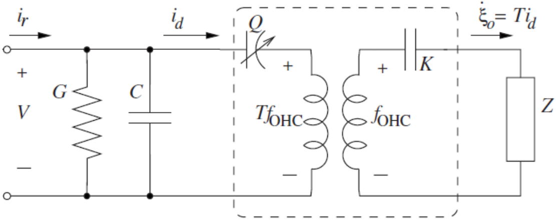
$$c(n+1) - c(n) = N(q(n), k(n)) - lc(n) - rc(n) \quad (2)$$

$$w(n+1) - w(n) = rc(n) - N(w(n), x) \quad (3)$$

The OHC Model



Liu and Neely Model - OHC Electromotility I



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- using Kirchhoff's current law:

$$i_r = C\frac{dV}{dt} + GV + C_g\frac{d\tilde{V}}{dt} \tag{4}$$

$$\tilde{V} = V - Tf_{OHC} \tag{5}$$

[8] Liu and Neely, "Distortion product emissions from a cochlear model with nonlinear mechanoelectrical transduction in outer hair cells." , vol. 127, pp. 2420–2432, Apr. 2010.

Liu and Neely Model - OHC Electromotility II

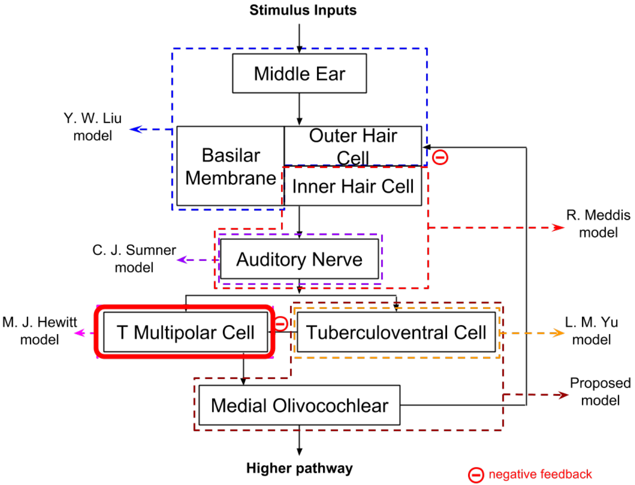
- OHC contraction displacement:

$$\xi_o = TQ \tag{6}$$

- contracting force:

$$f_{OHC} = M\ddot{\xi}_o + R\dot{\xi}_o + K\xi_o \tag{7}$$

The TM Model


Stimulus Inputs
Middle Ear
Y. W. Liu model
Basilar Membrane
Outer Hair Cell
Inner Hair Cell
R. Meddis model
C. J. Sumner model
Auditory Nerve
M. J. Hewitt model
T Multipolar Cell
Tuberculoventral Cell
L. M. Yu model
Proposed model
Medial Olivocochlear
Higher pathway
negative feedback

Hewitt et al. Model - Soma (TM Cell)

- transmembrane potential, $E(t)$:

$$\frac{dE(t)}{dt} = \frac{-E(t) + \{I_s(t)R_i + G_k(t)[E_k - E(t)]\}}{\tau_m} \tag{8}$$

- potassium conductance, $G_k(t)$:

$$\frac{dG_k(t)}{dt} = \frac{-G_k(t) + (bs)}{\tau_{Gk}} \tag{9}$$

- time-varying threshold, $\theta_{\mathrm{TM}}(t)$:

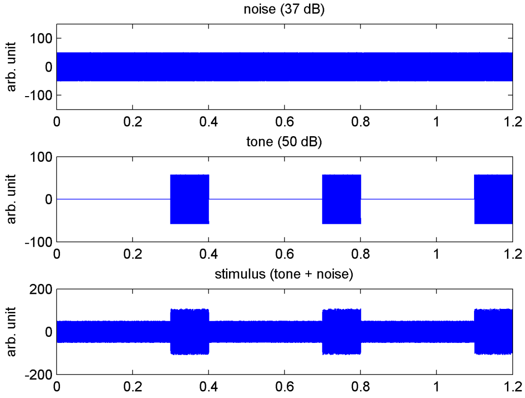
$$\frac{d\theta_{\mathrm{TM}}(t)}{dt} = \frac{-[\theta_{\mathrm{TM}}(t) - \theta_{0,\mathrm{TM}}] + cE(t)}{\tau_{\theta_{\mathrm{TM}}}} \tag{10}$$

- all-or-nothing spiking variable:

$$p(t) = E(t) + s[E_b - E(t)] \tag{11}$$

Proposed Model & Simulation Results

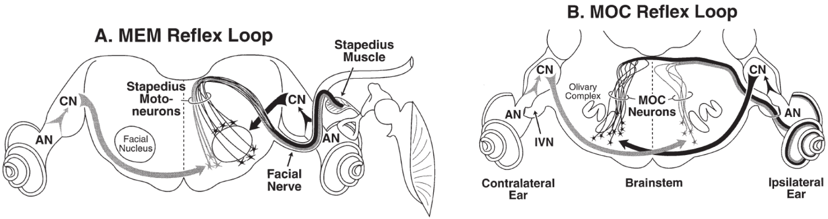
Simulating the Masking Effects



- noise: uniform distribution, 1200 ms, 37 dB SPL
- tone burst: 4000 Hz, 100 ms (begins at 300, 700, 1100 ms), from 0 to 100 dB SPL (with 10 dB steps)
- repeat 5 times for each tone level
- total $3 \times 5 = 15$ results

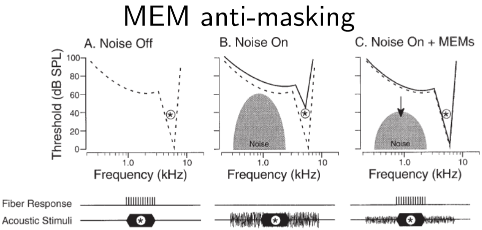
Anti-masking Effects

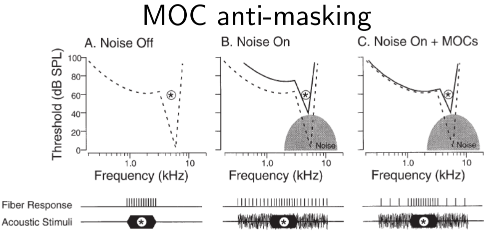
- There are two reflexes related to anti-masking[9]:
  - the middle ear muscles (MEM) reflex
  - the medial olivocochlear (MOC) reflex



[9] Liberman and Guinan, "Feedback control of the auditory periphery: anti-masking effects of middle ear muscles vs. olivocochlear efferents." , vol. 31, , 1998.

The MEM & MOC reflex Anti-masking

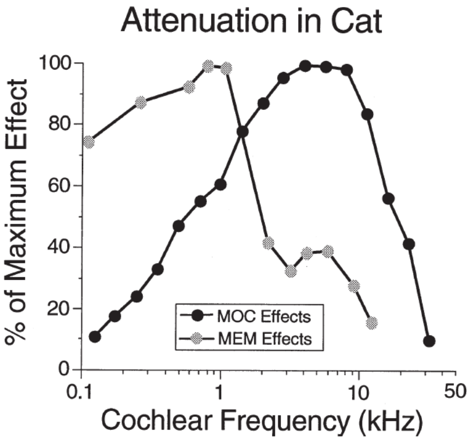




[10]

[10] Liberman and Guinan, "Feedback control of the auditory periphery: anti-masking effects of middle ear muscles vs. olivocochlear efferents." , vol. 31, , 1998.

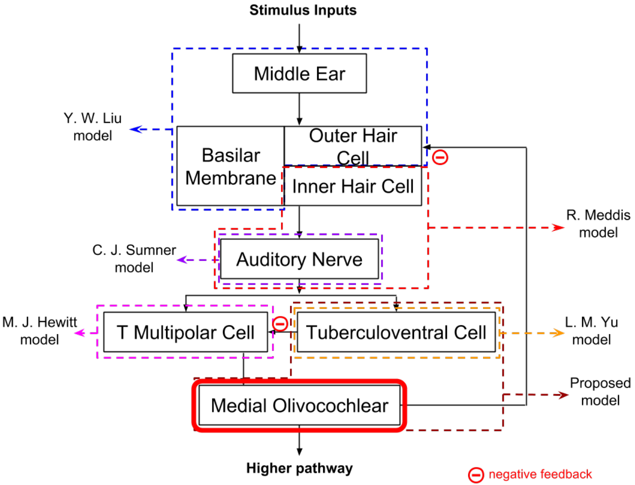
The anti-masking level



[11]

[11] Liberman and Guinan, "Feedback control of the auditory periphery: anti-masking effects of middle ear muscles vs. olivocochlear efferents." , vol. 31, , 1998.

The MOC Model



The Proposed MOC Anti-masking Model

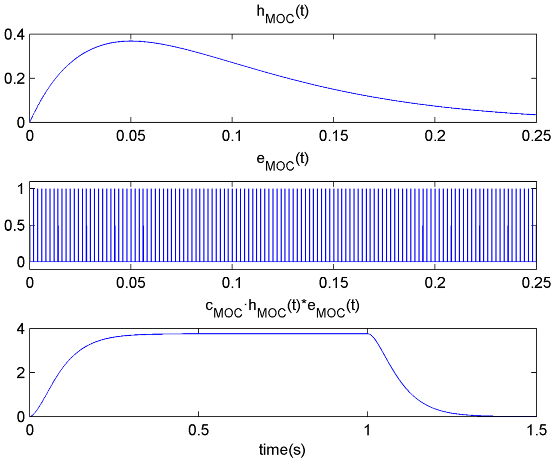
- raise the OHC conductance when the MOC receives excitations:

$$G_{\mathrm{OHC}}(x,t) = G_{0,\mathrm{OHC}}(x)\left[1 + c_{\mathrm{MOC}} \cdot h_{\mathrm{MOC}}(t) * e_{\mathrm{MOC}}(x,t)\right] \tag{12}$$

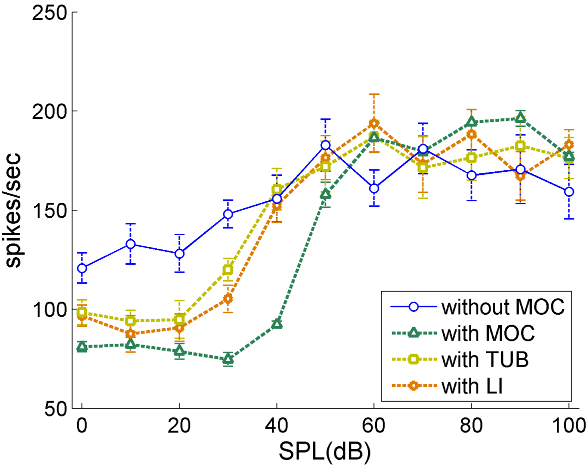
- convolution kernel:

$$h_{\mathrm{MOC}}(t) = \frac{t}{\tau_{\mathrm{MOC}}} e^{-\frac{t}{\tau_{\mathrm{MOC}}}} \tag{13}$$

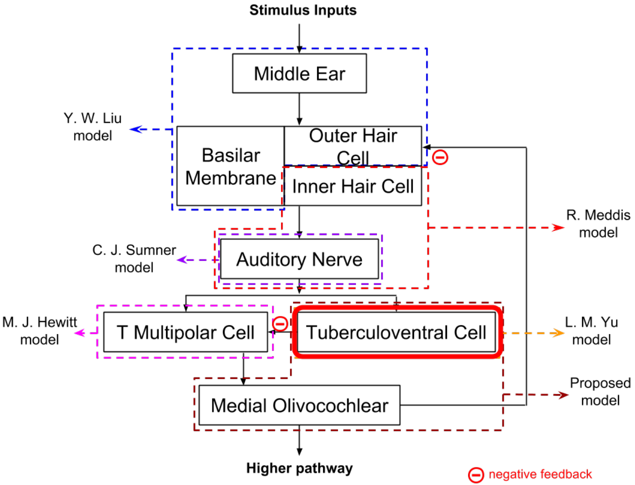
The MOC Convolution Kernel (Open Loop)



Closed Loop Simulation Results (Tone Burst)

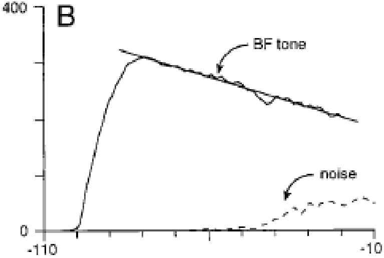


The TUB Model



The Tuberculoventral (TUB) Cell

- It is located in the deep layer of dorsal cochlear nucleus (DCN).
- The response to the tone decreases as the level increases above abuot 30 dB SPL.
- The response to noise is very low.



[12]

[12] Spirou, Davis, Nelken, *et al.*, "Spectral integration by type II interneurons in dorsal cochlear nucleus." , vol. 82, pp. 648–663, Aug. 1999.

The Proposed TUB Model - Inhibiting the TM

- raise the firing threshold of the TM:

$$\theta_{\mathrm{TM}}(x,t) = \theta_{0,\mathrm{TM}}(x) \cdot (1 + \mathrm{inh}_{\mathrm{TM}}(x,t)) \tag{14}$$

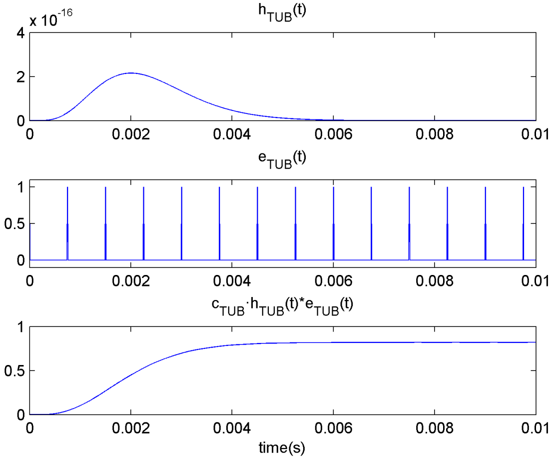
- the inhibitory level

$$\mathrm{inh}_{\mathrm{TM}} = c_{\mathrm{TUB}} \cdot h_{\mathrm{TUB}}(t) * e_{\mathrm{TUB}}(x,t) \tag{15}$$

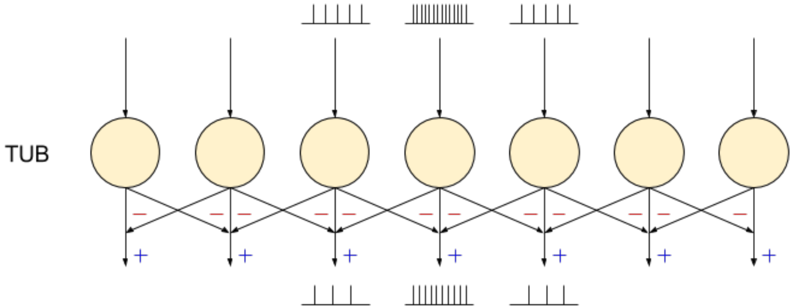
- convolution kernel:

$$h_{\mathrm{TUB}}(t) = \left(\frac{t}{\tau_{\mathrm{TUB}}} e^{-\frac{t}{\tau_{\mathrm{TUB}}}} \right)^5 \tag{16}$$

The TUB Convolution Kernel (Open Loop)



Lateral Inhibition



The Proposed TUB Model - Lateral Inhibition

- raise the firing threshold of the neighbor TUB:

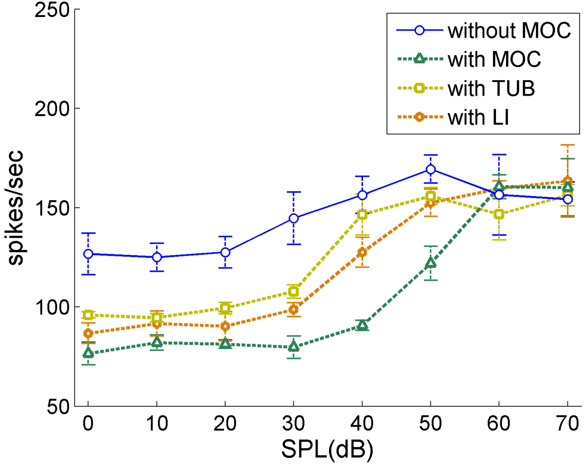
$$\theta_{\mathrm{TUB}}(x,t) = \theta_{0,\mathrm{TUB}}(x) \cdot (1 + \mathrm{inh}_{\mathrm{TUB}}(x,t)) \tag{17}$$

- the inhibitory level

$$\mathrm{inh}_{\mathrm{TUB}} = \frac{1}{c_{\mathrm{TUB}}} \cdot h_{\mathrm{TUB}}(t) * [e_{\mathrm{TUB}}(x-1,t) + e_{\mathrm{TUB}}(x+1,t)] \tag{18}$$

Sustained Tone-in-noise Condition (Closed loop)

- noise: uniform distribution, 1200 ms, 37 dB SPL
- tone: 4000 Hz, 1200 ms



Conclusion
&
Future Work

Conclusion I

- The proposed MOC model simulates the anti-masking effect in low tone-level region (< 50 dB), but not obvious in high level region (> 50 dB).
- The auditory discrimination is initially processed in this descending pathway with MOC.

Conclusion II

- In the tone-burst-in-noise condition, the RL curve with TUB and LI slightly shifts to the left but the range of distinguishable levels is not affected.
- In the sustained tone-in-noise condition, the distinguishable tone levels of RL curve is widened.
- The TUB model, which inhibits the TM cell, may help to make the RL curve become smoother, and enhances the discrimination ability between different tone levels.

Future Work

- Add other interneurons models in CN.
  - globular bushy cells
  - spherical bushy cells
  - octopus cells
- Consider other stimulus type and statistics.
  - speech
  - melody
  - peristimulus time histogram (PSTH)

The End
Thank You for Listening

This research is submitted as *"Close-loop Simulation of the Medial Olivocochlear Anti-masking Effects"* in Cosyne 2014.

Q & A

Supplementary Materials

Liu and Neely Model - Cochlear Mechanism

- Newton's second low:

$$\partial_x P = -\frac{\rho}{A}\dot{U} \tag{1}$$

- principle of continuity:

$$\partial_x U = w\dot{\xi}_r \tag{2}$$

- boundary conditions:

$$\partial_x P|_{x=0} = -\rho \dot{v}_s \tag{3}$$

$$\partial_x P|_{x=L} = \frac{-\rho}{Am_h} P \tag{4}$$

- the basilar membrane is driven by the membrain-fluid pressure:

$$m\ddot{\xi}_b + r\dot{\xi}_b + k\xi_b = -P \tag{5}$$

$$\xi_b = \xi_r + \xi_o \tag{6}$$

Liu and Neely Model - OHC Mechanoeletrical Transduction

- receptor current:

$$i_r = I(\eta) = \frac{I_{\max}}{2} \tanh \frac{2\eta}{I_{\max}} \tag{7}$$

$$\eta = \alpha_v \dot{\xi}_r + \alpha_d \xi_r \tag{8}$$

Sumner et al. Model - IHC receptor potential I

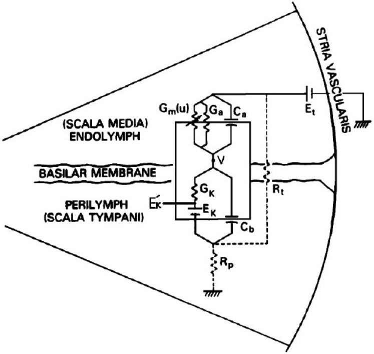
- IHC cilia displacement $u(t)$:

$$\tau_c \frac{du(t)}{dt} + u(t) = \tau_c C_{\mathrm{cilia}} v(t) \tag{9}$$

- apical conductance $G(u)$:

$$G(u) = \frac{G_{\mathrm{cilia}}^{\mathsf{max}}}{1 + \exp\left(-\frac{u(t)-u_0}{s_0}\right)\left[1 + \exp\left(-\frac{u(t)-u_1}{s_1}\right)\right]} + G_a \tag{10}$$

Sumner et al. Model - IHC receptor potential II



1

- using Kirchhoff's current law:

$$C_m \frac{dV(t)}{dt} + G(u)(V(t) - E_t) + G_k(V(t) - E_k') = 0 \quad (11)$$

[1] C. J. Sumner, E. A. Lopez-Poveda, L. P. O'Mard, *et al.*, "A revised model of the inner-hair cell and auditory-nerve complex.," *The Journal of the Acoustical Society of America*, vol. 111, no. 5 Pt 1, pp. 2178–2188, May 2002.

Sumner et al. Model - Calcium Controlled Transmitter Release Function I

- calcium current:

$$I_{\mathrm{Ca}}(t) = G_{\mathrm{Ca}}^{\mathsf{max}} m_{I_{\mathrm{Ca}}}^3(t)(V(t) - E_{\mathrm{Ca}}) \tag{12}$$

- fraction of opened calcium channels, $m_{I_{\mathrm{Ca}}}(t)$:

$$\tau_{I_{\mathrm{Ca}}} \frac{dm_{I_{\mathrm{Ca}}}(t)}{dt} + m_{I_{\mathrm{Ca}}}(t) = m_{I_{\mathrm{Ca}},\infty} \tag{13}$$

$$m_{I_{\mathrm{Ca}},\infty} = \frac{1}{1 + \frac{1}{\beta_{\mathrm{Ca}}} e^{-\gamma_{\mathrm{Ca}} V(t)}} \tag{14}$$

Sumner et al. Model - Calcium Controlled Transmitter Release Function II

- calcium concentration:

$$\tau_{[\mathrm{Ca}]}\frac{d[\mathrm{Ca}^{2+}](t)}{dt} + [\mathrm{Ca}^{2+}](t) = I_{\mathrm{Ca}}(t) \qquad (15)$$

- transmitter release rate function:

$$k(t) = \max(([\mathrm{Ca}^{2+}]^3(t) - [\mathrm{Ca}^{2+}]^3_{\mathrm{thr}})z, 0) \qquad (16)$$

Hewitt et al. Model - Dendrite (TM Cell)

- summation of dendrite inputs from ANs:

$$I_d(t) = n(t)\Delta I \tag{17}$$

- Butterworth low-pass filtering:

$$I_s[n] = GI_d[n] + GI_d[n-1] - HI_s[n-1] \tag{18}$$

$$G = \frac{1}{1 + \frac{1}{\tan\left(\pi \frac{f_c}{f_s}\right)}} \tag{19}$$

$$H = \frac{1 - \frac{1}{\tan\left(\pi \frac{f_c}{f_s}\right)}}{1 + \frac{1}{\tan\left(\pi \frac{f_c}{f_s}\right)}} \tag{20}$$