Modeling the Neural Representation of Interaural Level Differences for Linked and Unlinked Bilateral Hearing Aids

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ABSTRACT

Interaural level difference (ILD) cues facilitate horizontal localization of sound frequencies above ~ 1.5 kHz and are processed by the lateral superior olive (LSO) of the brainstem. The LSO is excited by sounds that are louder in the ipsilateral ear than in the contralateral ear. Bilateral hearing aids with independent wide dynamic range compression (WDRC) will tend to reduce the ILD cues. Hearing aids with wirelessly-linked WDRC algorithms are reported to have varying levels of success in restoring or maintaining an individual's ability to understand and localize sounds. In our study, we model the neural processing of the LSO in response to linked and unlinked WDRC schemes.

Two computer models are used to predict LSO responses. The first is a phenomenological model that takes inputs directly from ipsilateral and contralateral outputs of an auditory nerve (AN) model [12, 13]. The LSO response is estimated from the difference in AN spike rates and a sigmoidal nonlinearity to account for the threshold and saturation in LSO spike rates. The second is a Hodgkin–Huxley-type biophysical model, which details the ion channel behavior of LSO cells. Inputs to this model are excitatory and inhibitory synaptic currents derived from the outputs of the ipsilateral and contralateral AN models, respectively. Both normal-hearing and hearing-impaired responses are generated. AUDIS [2] head-related transfer functions are used to simulate sound sources ranging from $-80°$ to $+80°$ on the horizontal plane.

Unlinked WDRC degrades the coding of sound source azimuth in the LSO by reducing ILDs. Wirelessly linked hearing aids maintain ILD cues and have the potential to enable the LSO response to indicate azimuth, provided sufficient gain and appropriate compression time constants. These results will contribute to our understanding of the azimuthal perception of sounds at the neuronal level. This has implications for the design of hearing aids to provide optimal spatial awareness to the listener.

I. INTRODUCTION

A. Interaural Level Difference

- Auditory localization is important for safe functioning in everyday environments and is a factor in speech intelligibility.
- Azimuthal localization is facilitated by interaural timing difference (ITD) cues, which are most perceptually salient for low-frequency sounds (below 1500 Hz), while interaural level difference (ILD) cues are predominant for high-frequency sounds [1].
- ILDs are a product of the acoustic head shadow; sounds are attenuated at the farther, shadowed ear relative to the closer, unshadowed ear (Fig. 1(L)).

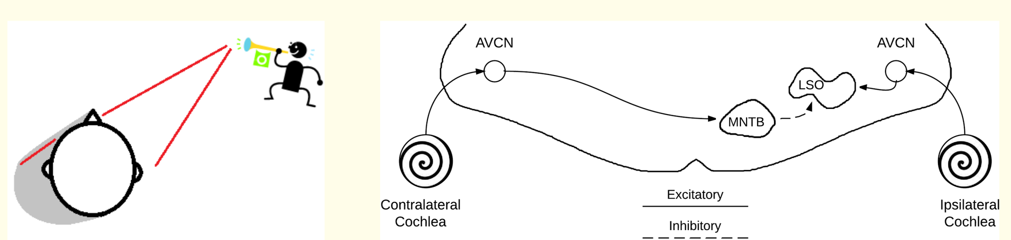

Figure 1: *[Left]: ILD cues arise from the head shadow effect. [Right]: Neural processing of ILD cues occurs in the lateral superior olive (LSO).*

- Sensorineural hearing impairment reduces dynamic range: Binaural cues for localization may be less salient, such that no benefit can be derived.

B. Wireless Wide Dynamic Range Compression

- Wide dynamic range compression (WDRC) hearing aids typically skew ILD cues by applying differing gains to the two bilateral devices.
- Wireless technologies allow communication between bilateral devices so that the gain applied at each ear is dependent on the levels at both ears.
- In one scheme under investigation, linked amplification applies the lowest gain required by either of the two [11].
- Performance with these devices is varied.

Table 1: *Reports on wireless WDRC benefit are varied.*

Author	Measure and Test	Conclusions
Ibrahim et al., 2012 [4]	Sound localization Speech intelligibility	Improved localization. No benefit to speech-in-noise scores.
Sockalingham, 2009 [8]	Sound localization Quality	Improved localization. Improved naturalness only in certain environments.
Wiggins and Seeber, 2013 [11]	Speech intelligibility	Improved performance is due to improved SNR at worse ear, not wireless link.
Schwartz and Shinn-Cunningham, 2013 [6]	Spatial thresholds	Improved localization for fast attack and release times. No trend in slow WDRC.
Smith, 2008 [7]	Preference	65% prefer wirelessly-linked WDRC.

C. The Neural Pathway for ILD Cues

- ILD cues are analyzed in the lateral superior olive (LSO) of the brainstem.
- The LSO receives inhibitory inputs from the contralateral anteroventral cochlear nucleus (AVCN) and excitatory inputs from the ipsilateral AVCN (Fig. 1(R)).
- LSO cells are tonotopically mapped and are excited by greater intensity in the ipsilateral ear.
- The relationship between ILD and excitation (discharge rate in spikes/s) is sigmoidal.
- Some suggest that the sigmoidal tuning function shifts with respect to overall levels of sound presentation, although other studies find ILD thresholds to be level-invariant [9].

II. METHODS

- LSO representations of stimuli were modelled for an ideal normal-hearing listener and an example hearing-impaired listener.

A. Hearing Aid Model

- A model of a simple, unilateral WDRC hearing aid was programmed in MATLAB.
- A separate script allowed for simulated wireless linking between two hearing aids, assuming instantaneous communication.
- The model uses overlap-and-add, applying amplification in the frequency domain.

B. Auditory Periphery Model

- An existing model of the auditory periphery [12, 13] was used to generate ipsilateral and contralateral AN spike trains.
- Inner and outer hair cell control parameters are adjusted to reflect the listener's audiogram.

C. Phenomenological Model of the Lateral Superior Olive

- A phenomenological model of the lateral superior olive was programmed to simulate the sigmoidal relationship between ILD and spike rate.
- The sigmoidal tuning function is defined as:

$$y = a + \frac{b}{1+\exp\frac{c-x}{d}} \tag{1}$$

- y is LSO spike rate and x is the difference between ipsilateral and contralateral AN inputs.
- Parameters a, b, c, and d are chosen to give spike rates consistent with Tsai et al. [9]

D. Biophysical Model of the Lateral Superior Olive

- A Hodgkin–Huxley-type biophysical model of the LSO was also used, guided by the ventral cochlear nucleus Hodgkin–Huxley models of Rothman and Manis [5].
- Ion channel parameters were adapted from Wang and Colburn [10].

$$C_m \frac{\mathrm{d}V}{\mathrm{d}t} = I_A + I_{\mathrm{LT}} + I_{\mathrm{HT}} + I_{\mathrm{Na}} + I_h + I_{\mathrm{lk}} + I_{\mathrm{Exc}} + I_{\mathrm{Inh}} \tag{2}$$

- Currents are as follows:

Table 2: *Currents of the Hodgkin–Huxley-type biophysical LSO model.*

Notation	Current Type
I_A	fast-inactivating K^+ current
I_{LT}	low-threshold K^+ current
I_{HT}	high-threshold K^+ current
I_{Na}	Na^+ current
I_h	hyperpolarization-activated cation current
I_{lk}	leakage current
I_{Exc}	excitatory synaptic current (i.e. ipsilateral AN input)
I_{Inh}	inhibitory synaptic current (i.e. contralateral AN input)

E. Listener Models

- The Wiggins and Seeber [11] hearing-impaired audiogram and CAMEQ fit were used for the hearing-impaired model.
- The normal-hearing model assumed completely undamaged inner and outer hair cells.

Table 3: *Hearing-impaired audiogram from Wiggins and Seeber [11].*

Audiogram										
Frequency (Hz)	250	375	500	750	1000	1500	2000	3000	4000	6000
dB HL	35	35	35	35	40	45	50	55	60	65

Table 4: *Hearing aid prescription as set by Wiggins and Seeber [11].*

Channel	Lower Edge Frequency	Upper Edge Frequency	Compression Threshold	Compression Ratio	IG50	IG80
1	125	250	46	1.53	10.2	0.0
2	250	750	47	1.11	10.3	7.4
3	750	1250	40	1.99	20.8	5.9
4	1250	1750	30	1.89	20.5	6.4
5	1750	2250	27	1.98	22.9	8.0
6	2250	2750	28	2.01	21.7	6.6
7	2750	3250	27	1.99	20.7	5.8
8	3250	3750	24	1.99	21.4	6.5
9	3750	4250	20	2.01	22.2	7.1
10	4250	4750	22	2.22	21.6	5.1
11	4750	5250	21	2.51	20.8	2.8
12	5250	5750	22	2.80	20.2	1.0

F. Stimuli

- A 4 kHz puretone stimulus was used with a duration of 2 s and 5-ms on and off ramps.
- A sentence of Northern American-accented speech from the TIMIT corpus was also used: *"She had your dark suit in greasy wash water all year"*.
- Stimuli were presented at azimuths ranging from $-80°$ to $+80°$.
- AUDIS HRTFs were used to generate realistic ILD cues [2].

G. Test Conditions

- For the normal-hearing model, only unaided listening was tested.
- For the hearing-impaired model, simulations included: unaided hearing; linked, bilateral WDRC; and unlinked, bilateral WDRC.
- In the aided conditions, three sets of compression times were used:
  - Wiggins and Seeber "WS" (5 ms attack, 60 ms release) for all stimuli [11].
  - Very Fast (1 ms attack, 10 ms release) for the TIMIT sentence.
  - Slow (100 ms attack, 400 ms release) for the TIMIT centence.
- Attack and release time choices were guided by Dillon [3].

Table 5: *Test Conditions. P denotes use of the phenomenological model and B of the biophysical model.*

Stimulus		Normal-Hearing	Hearing-Impaired						
			No WDRC	Unlinked WDRC			Linked WDRC		
				WS	Very Fast	Slow	WS	Very Fast	Slow
Puretone	35 dB SPL	P/B	P	P			P		
	45 dB SPL	P	P	P			P		
	55 dB SPL	P	P	P			P		
	65 dB SPL	P/B	P	P			P		
	75 dB SPL	P	P	P			P		
	85 dB SPL	P/B	P	P			P		
TIMIT Speech		P	P	P	P	P	P	P	P

H. Measure: Mean Discharge Rate Difference

- The mean discharge rate difference was calculated to quantify the degree of similarity to which the hearing-impaired model performed, relative to the normal-hearing model.

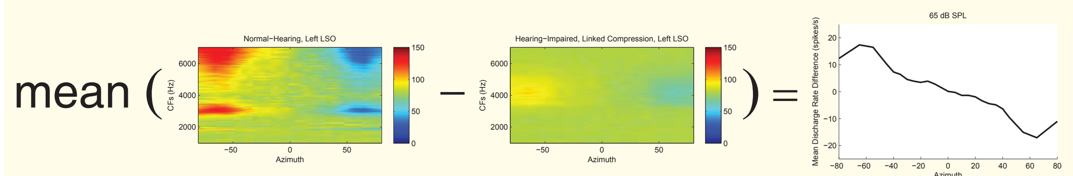

Figure 2: *Calculation of the mean discharge rate difference over CF.*

III. RESULTS

A. ILD Cue Distortion

- Linked WDRC retains ILD cues (Fig. 3 A).
- Unlinked compression reduces ILD cues, and the reduction varies with presentation level (Fig. 3 B).

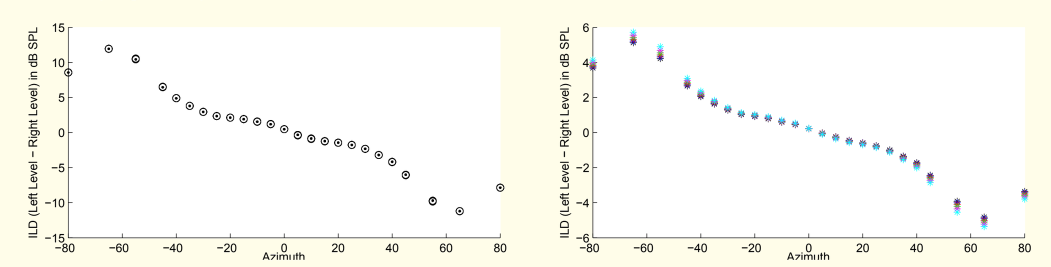

Figure 3: *[Left]: Linked WDRC retains ILD cues. Dots denote natural ILDs. Open circles denote linked ILDs. [Right]: Unlinked WDRC distorts ILD cues to an extent variable with presentation level. Black: 35 dB SPL; Blue: 45 dB SPL; Red: 55 dB SPL; Green: 65 dB SPL; Magenta: 75 dB SPL; Cyan: 85 dB SPL*

B. Puretone Stimuli Results

- In the hearing-impaired model, linked compression performs most similarly to the normal-hearing model for all puretone stimuli.
- The impact of WDRC is greatest near 55 – 65 dB SPL and least at low frequencies.
- Unaided listening results in the most different neural representations from normal hearings at all levels but 85 dB SPL.
- At 85 dB SPL, unlinked WDRC is worse than unaided listening.
- Normal-hearing discharge rates exceed all discharge rates for impaired hearing (Fig. 5).

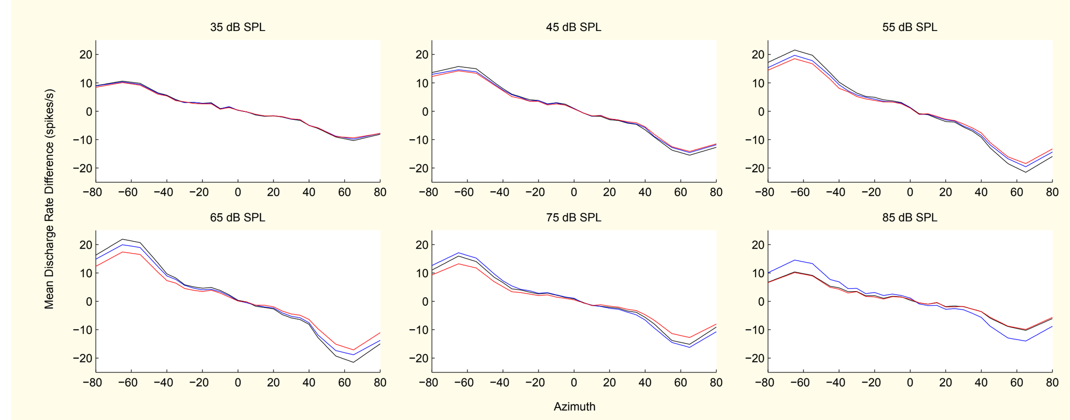

Figure 4: *LSO mean differences under the phenomenological model in spikes/s. The following hearing-impaired neural representations are subtracted from the normal-hearing response, and denoted as follows: Black: unaided; Blue: unlinked WS WDRC; Red: linked WS WDRC.*

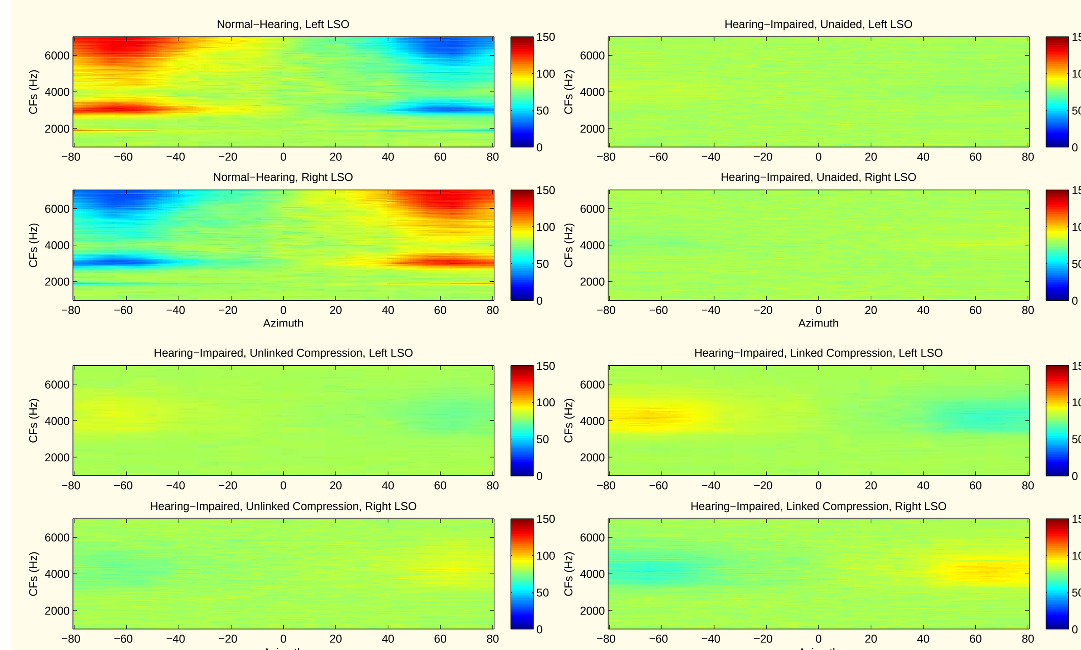

Figure 5: *An example of patterns of neural response to ILD cues (65 dB SPL puretone stimulus). Normal-hearing spike rates are higher than those in the hearing-impaired model for all compression conditions.*

C. TIMIT Sentence Results

- No compression condition consistently results in the lowest mean difference scores (Fig. 6).
- Not all phones contain enough energy to trigger WDRC (Fig. 7).
- WDRC benefit varies within phone class; frequency band energy is not the only indicator of performance.
- Phone placement is important:
  - In all stop closures but 'gcl', which immediately followed a nasal, spike rates for the hearing-impaired model exceeded those of the normal-hearing model (8).

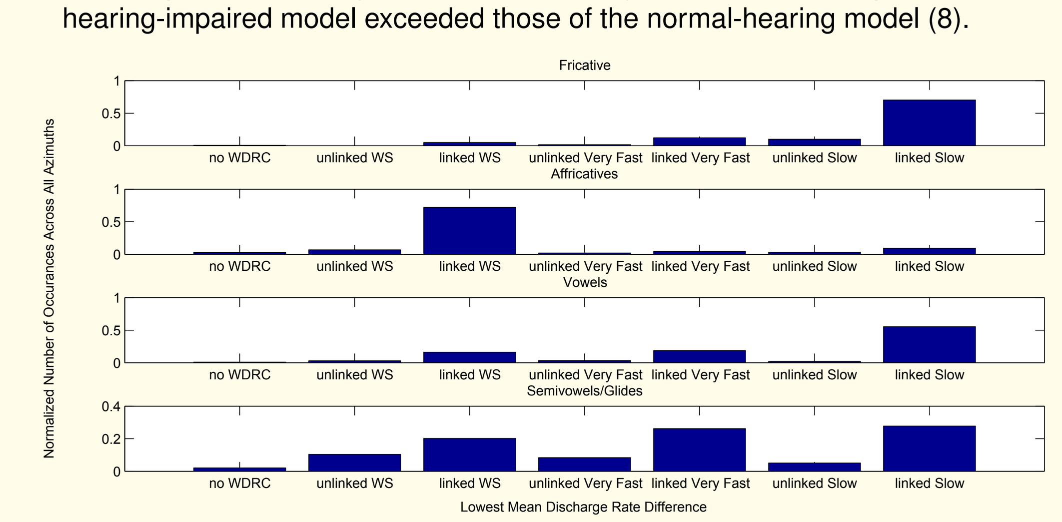

Figure 6: *Neither linked nor unlinked WDRC is consistently preferable for speech sounds, although linked is often better. No particular set of compression speeds is consistently best.*

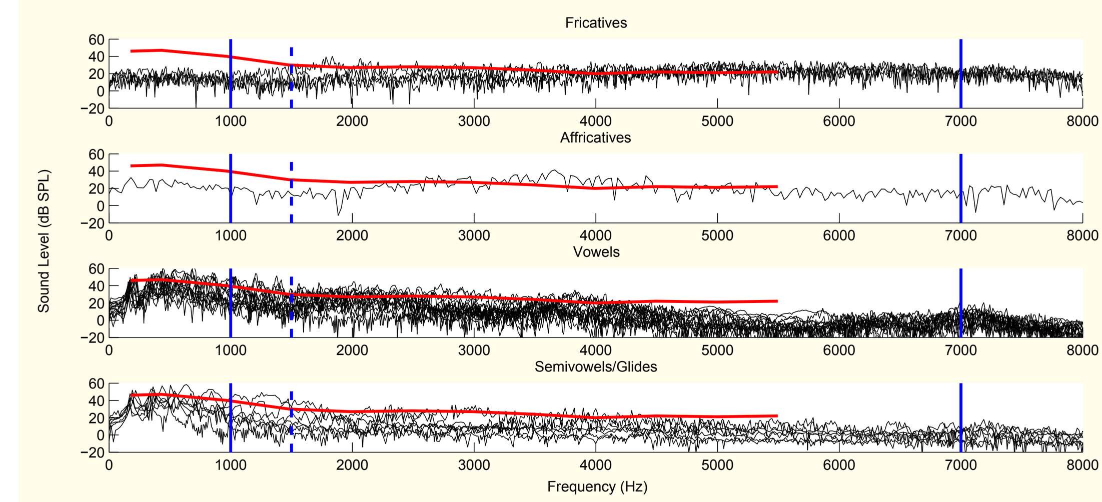

Figure 7: *Energy in some phones of the TIMIT sentence. Solid blue lines indicate the range of AN fiber CFs modelled, while the dashed blue line indicates the 1500 Hz boundary between low and high frequencies. The red curve denotes the compression threshold.*

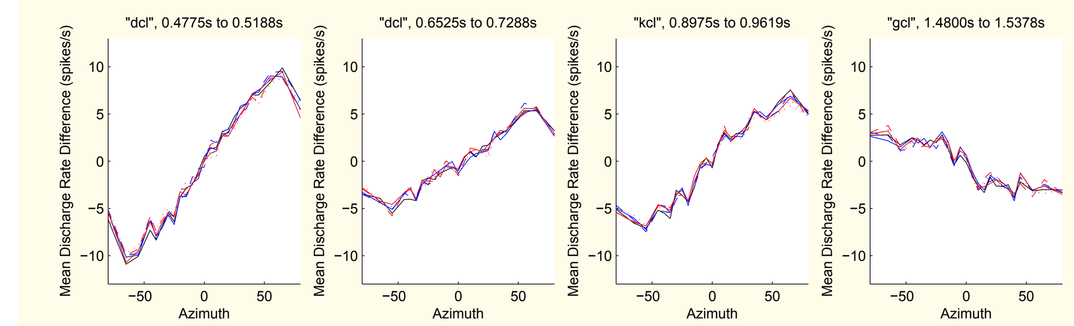

Figure 8: *Phone placement seems to impact WDRC performance. The following hearing-impaired neural representations are subtracted from the normal-hearing response, and denoted as follows:- Black: unaided; Blue: unlinked WDRC; Red: linked WDRC. Compression speeds are denoted as follows:- Solid lines: WS compression; Dashed lines: Very Fast compression; Dotted lines: Slow compression.*

IV. CONCLUSIONS

- The benefit of linked WDRC over unlinked WDRC is clear for puretone stimuli.
- In speech stimuli, the benefit is dependent on frequency content, presentation level, phone class, and phone placement within a sentence.
- Adaptive attack and release times may show the most promise as this technology continues to develop.

V. ACKNOWLEDGMENTS

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REFERENCES

[1] M. A. Akeroyd, "The psychoacoustics of binaural hearing," *International Journal of Audiology*. Volume 45, Issue S1, pgs. 25-33, 2006.

[2] J. Blauert et al., "The AUDIS catalog of human HRTFs," *The Journal of the Acoustical Society of America*. Volume 103, Issue 5, pgs. 3082-3082, May 1998.

[3] H. Dillon, *Hearing Aids (Second Edition)*. Turramurra, Australia: Boomerang Press, 2012.

[4] I. Ibrahim et al., "Evaluation of speech intelligibility and sound localization abilities with hearing aids using binaural wireless technology," *Audiology Research*. Volume 3, Issue 1, pgs. 1-9, December 2012.

[5] J. S. Rothman And P. B. Manis, "The Roles Potassium Currents Play in Regulating the Electrical Activity of Ventral Cochlear Nucleus Neurons," *Journal of Neurophysiology*. Volume 89, Issue 6, pgs. 3097-3113, February 2003.

[6] A. H. Schwartz and B. Shinn-Cunningham, "Effects of dynamic range compression on spatial selective auditory attention in normal-hearing listeners," *The Hearing Journal*. Volume 133, Issue 4, pgs. 2329-2339, 2013.

[7] P. Smith et al., "Real-world preferences for linked bilateral processing," *The Hearing Journal*. Volume 61, Issue 7, pgs. 33-34, July 2008.

[8] R. Sockalingham et al., "Binaural hearing aid communication shown to improve sound quality and localization," *The Hearing Journal*. Volume 62, Issue 10, pgs. 46-47, October 2009.

[9] J. J. Tsai et al., "Varying Overall Sound Intensity to the Two Ears Impacts Interaural Level Difference Discrimination Thresholds by Single Neurons in the Lateral Superior Olive," *Journal of Neurophysiology*. Volume 103, Issue 2, pgs. 875-886, February 2010.

[10] L. Wang et S. Colburn, "A Modeling Study of the Responses of the Lateral Superior Olive to Ipsilateral Sinusoidally Amplitude-Modulated Tones," *Journal of the Association for Research in Otolaryngology*. Volume 13, Issue 2, pgs. 249-267, April 2012.

[11] I. M. Wiggins and B. U. Seeber, "Linking dynamic-range compression across the ears can improve speech intelligibility in spatially separated noise," *The Journal of the Acoustical Society of America*. Volume 133, Issue 2, pgs. 1004-1016, 2013.

[12] M. S. A. Zilany et al., "Improved parameters and expanded simulation options for a model of the auditory periphery," *Abstracts of the 36th ARO Midwinter Research Meeting*. Association for Research in Otolaryngology. Baltimore, MD, pgs. 440-441, 2013.

[13] M. S. A. Zilany et al., "A phenomenologicial model of the synapse between the inner hair cell and auditory nerve: Long-term adaptation with power-law dynamics," *Journal of the Acoustical Society of America*. Volume 126, Issue 5, pgs. 2390-2412, 2009.