Award: N000141512140

Behavioral Measures of the Precision of Coding of Interaural Temporal Disparities (ITD) in Human Listeners

PI: Leslie R. Bernstein

Final Technical Report

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PI: Leslie R. Bernstein
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University of Connecticut Health Center

Final Technical Report

Naval Relevance

The potential Naval relevance is the anticipated development of a straightforward test or series of tests to identify central, binaural manifestations of noise-induced hearing loss. The binaural system plays a fundamental and predominant role in our ability to localize sounds, to understand conversation in noisy operational and/or reverberant environments, and to attend to one of multiple, simultaneous sounds. Appropriate binaural testing can serve as a diagnostic tool that permits detection of insipient degradations of the binaural processing that underlies our ability to detect, to locate, to differentiate between, and to identify sources of sound. **Those basic abilities, in turn, underlie and/or mediate the ability of warfighters to have situational awareness and to communicate with each other in the complex and noisy environments that are often part and parcel of their working environments**.

Final Technical Report: 15 June 2015 – 23 January 2019

I. Major Goals

The major goals of the project were those described in the original proposal. Those objectives stemmed from the recognition that ongoing interaural (between ear) temporal disparities (ITDs) of sounds are the primary binaural cue supporting the ability to localize sounds, to understand conversation in noisy and/or reverberant environments, and to attend to one of multiple, simultaneous sounds. Surprisingly little was known regarding how the precision of the “internal” coding of ITDs varies with their magnitude (related to a sound’s azimuthal position) and the frequency region of the sound. A primary objective was to characterize that precision. While such fundamental aspects of ITD-processing were poorly understood for young, normal-hearing listeners, even less was understood regarding how degradations of ITD coding may be age-related and/or may be associated with, or result from even “slight” hearing-loss. Liberman and his colleagues demonstrated that peripheral neural coding deficits may occur even when audiometric sensitivity is normal (“hidden” hearing-loss). Behavioral manifestations of such losses in human listeners had, to date, been rather elusive. Our early findings had strongly suggested that we had discovered a central, binaural, ITD-related neural manifestation of such deficits. Thus, another primary objective was to measure and characterize those manifestations. Finally, a major objective was to account for the newly gathered empirical data via a historically successful, comprehensive, quantitative, cross-correlation-based model of binaural hearing.

II. Approach

The experiments conducted utilized a novel set of stimulus configurations to measure binaural signal detection and binaural discrimination. Those configurations yield converging measures designed to reveal how precision of ITD-coding changes as a function of both reference ITD and the center frequency of the stimuli. Using stimuli with center frequencies over the range 125 Hz to 8 kHz, detection and discrimination thresholds were measured for a group of human listeners aged between about 25 and 60 years and all having audiometric thresholds no greater than those characterized as “slight loss.” The data and their statistical analyses allow us to address the major goals described above.

III. Period 1: 1-June-2015 – 14-June-2016

a. Results Dissemination

The results were disseminated via publications in journals including the *Journal of the Acoustical Society of America* and via presentations at national/international meetings.

Publications:

Bernstein L. R. and Trahiotis C. (2015). “Converging measures of binaural detection yield estimates of precision of coding of interaural temporal disparities,” J. Acoust. Soc. Am. 138, EL474-479.

Bernstein L. R. and Trahiotis C. (2016). “Behavioral manifestations of audiometrically-defined ‘slight’ or ‘hidden’ hearing loss revealed by measures of binaural detection,” J. Acoust. Soc. Am. (submitted)

Presentations:

Bernstein L. R. and Trahiotis C. “The putative internal delay line: Seeking some resolution,” Binaural and Spatial Hearing (BASH). International Conference held at Boston University; 2015 Oct 30-31 (Invited)

Bernstein L. R. and Trahiotis C. “Precision of Coding of Interaural Delay: Interesting Observations re Age and Hearing-Status,” 39^{th} Annual Midwinter Meeting of the Association for Research in Otolaryngology; 2016 Feb 20-24; San Diego

b. Accomplishments/Progress
(Note: Figure numbering starts anew within each reporting period)

During the first reporting period, substantial progress was made including: 1) screening and recruitment of human subjects; 2) gathering empirical data; 3) development of quantitative, theoretical accounts of the data; 4) publication and presentation of results.

Project Startup

The effective start-date of the project was June 1, 2015. Within one month, a new research assistant, was hired, in-place, and began training. Simultaneous with those efforts, recruitment of subjects was begun as well as arrangement for their screening and clinical audiograms.

Empirical and theoretical findings

The large-scale set of binaural detection experiments proposed was well underway by the end of the reporting period. That set of experiments employed a novel set of three stimulus configurations that yield converging measures of binaural detection that allow one to describe the precision of the coding of interaural temporal disparities across center frequency.

One of the stimulus configurations begins with the classic NoSπ stimulus configuration in which the noise masker is presented identically to the two ears and a tonal signal is presented interaurally 180° out of phase. The novel enhancement is to measure detection thresholds after the imposition of an interaural delay on the entire NoSπ signal-plus-masker waveform. We refer to this new stimulus configuration as $(NoS\pi)_\tau$. If it were the case that the listener could compensate “internally” perfectly for the imposed interaural delay, effectively cancelling it and transforming it back to NoSπ, then thresholds of detection would remain constant regardless of the magnitude of the interaural delay. On the other hand, if precision of ITD-coding declines with increasing magnitude of ITD, then thresholds of detection would be expected to increase with increasing magnitude of ITD, an outcome that would, presumably, be a manifestation of increasing processing noise along the putative internal delay line.

The second configuration, referred to as (No)±τ(Sπ)τ, is called the “double delay” configuration The double-delayed noise masker is composed of the sum of two independent noises, one interaurally delayed toward the left ear and the other interaurally delayed by an equal amount toward the right ear. Within the double-delay configuration, the Sπ signal is also delayed by τ. The double-delayed noise has precisely the same interaural correlation as its “single-delayed” counterpart. Because the double-delayed noise incorporates two opposing, “mirror image” interaural delays, there exists no single delay that can be employed by the listener in order to transform (No)±τ(Sπ)τ back to NoSπ. That is, the listener cannot internally cancel the delay.

The third stimulus configuration, (NoSo)τ, begins with the standard NoSo stimulus configuration in which the noise masker and signal are each presented identically to the two ears. Detection thresholds are then measured after the imposition of an interaural delay on the entire NoSo signal-plus-masker waveform. Because there are no binaural cues available to aid detection, the (NoSo)τ configuration serves as a control condition and allows one to determine if changes in the lateral position of the intracranial image resulting from the imposition of the interaural delay (τ), per se, affects detection.

Figure 1 shows the data reported in Bernstein and Trahiotis (2015). In that study, detection thresholds were measured for three adult listeners in the (NoSπ)τ, (No)±τ(Sπ)τ, and (NoSo)τ configurations for 250-Hz, Sπ tonal signals masked by 50-Hz-wide Gaussian noises centered at 250 Hz (panel a) or when those stimuli were transposed to 4 kHz (panel b).

In each panel, the data, averaged across listeners, reveal that: 1) detection thresholds obtained using the (NoSo)τ configuration (squares) are essentially constant, thereby indicating that the laterality (intracranial position) of the stimuli, per se, does not affect performance; 2) detection thresholds obtained using the (No)±τ(Sπ)τ configuration (triangles) are cyclical in nature and are equivalent to those measured with the (NoSo)τ for ITDs of 1000 and 3000 μs; 3) detection thresholds obtained using the (NoSπ)τ configuration (circles) increase from a signal-to-noise ratio of about -18 dB to about -10 dB as ITD (τ) is increased from 0 to 3000 μs and then decrease slightly to -13 dB as the ITD is increased further to 4000 μs.

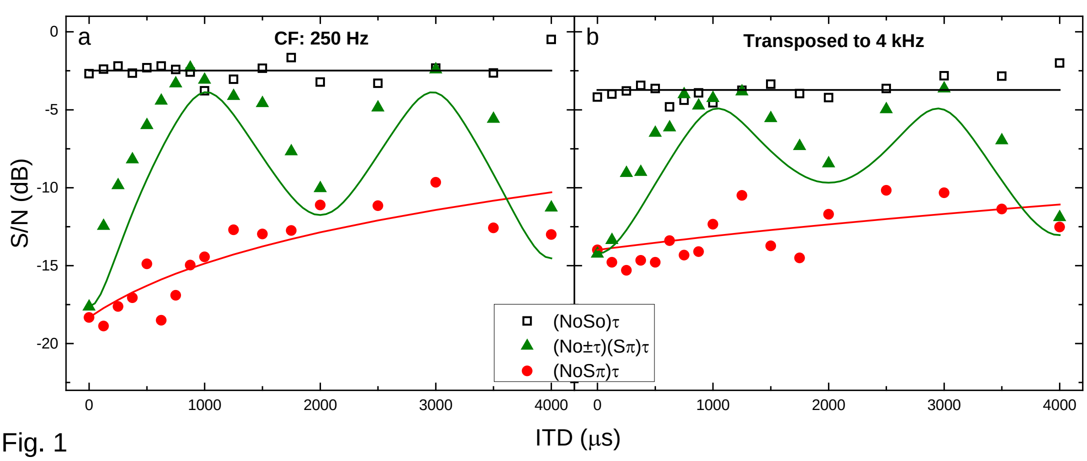

Fig. 1

The thresholds obtained in the (No)±τ(Sπ)τ stimulus conditions conform to what would be expected when compensation of ITD cannot occur and when listeners base their decisions on changes in interaural correlation. The lower thresholds obtained in the (NoSπ)τ stimulus conditions, as compared to those obtained in the (No)±τ(Sπ)τ stimulus conditions indicate that ***compensation of ITD does***

occur and appears to be accomplished less precisely as ITD in increased. Overall, the data in panels a and b indicate that precision of ITD-processing can be isolated from other factors and measured as a function of baseline ITD for low-frequency stimuli for which the fine-structure conveys the temporal information and for high-frequency stimuli for which the envelope conveys the temporal information.

The lines within each panel of the figure represent predictions derived in the following manners: 1) for (NoSo)τ, the lines representing the mean of the thresholds obtained across ITD are horizontal and reflect the assumption that, because detection cannot be based on binaural cues ITD would be expected to play no role; 2) for (No)±τ(Sπ)τ, the lines represent predictions made under the assumptions that no compensation of ITD occurs and that decisions are based on changes in interaural correlation of the masker produced by the addition of the signal; 3) for (NoSπ)τ, the lines represent predictions made assuming that "noisy" compensation of ITD occurs and that, subsequent to such compensation, decisions are based on changes in interaural correlation of the masker produced by the addition of the signal.

Additional progress was demonstrated by the results of an experiment that employed a subset of the larger set of experimental conditions proposed. The subset was run simultaneously with the larger experiment and the goal was to focus quickly on conditions that appear to ***reveal degraded binaural precision in the face of slight hearing-losses and, perhaps, with advancing age.***

Figure 2 displays detection thresholds averaged across 31 listeners whose ages spanned the range of about 25 to 60 years, all of whom would be considered to have no more than "slight" hearing loss. The experimental configurations are the same three as those described above. The left panel displays thresholds obtained for tonal stimuli and 900-Hz-wide noise maskers centered at 500 Hz; the right panel displays thresholds for tonal stimuli and 50- or 100-Hz-wide maskers centered at 125 Hz and then transposed to 4 kHz. The error bars represent ±1 se and the parameter within each panel is stimulus configuration.

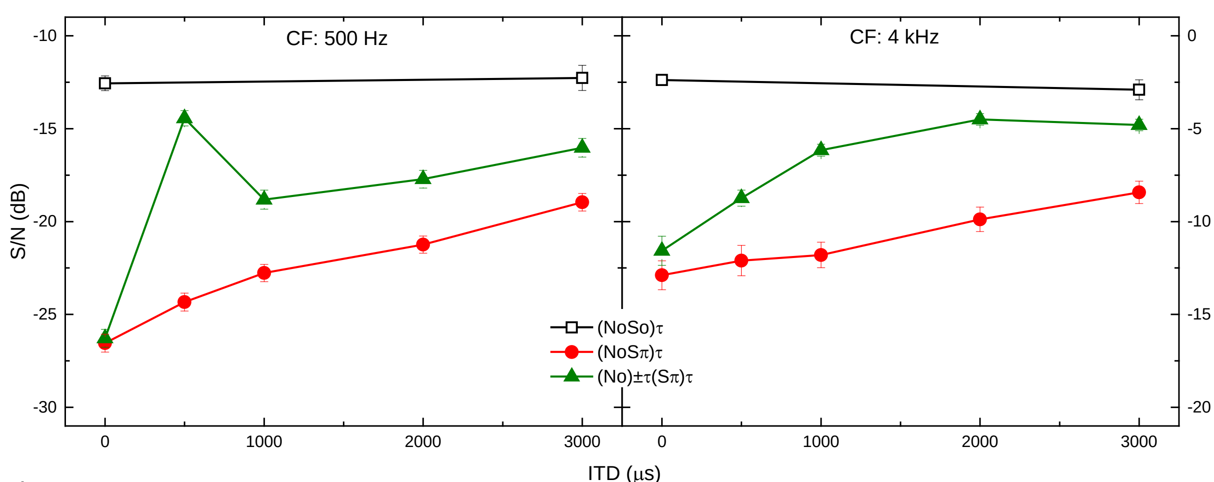

Fig. 2

As expected, the same hierarchy of thresholds as observed in Fig. 1 is observed in Fig. 2. The salient outcomes are: 1) (NoSo)τ thresholds obtained at each, respective, center frequency with ITDs of 0 and 3000 µs are essentially identical, indicating that imposing an ITD had no effect on detectability; 2) at each center frequency, (NoSπ)τ thresholds increase monotonically with magnitude of ITD. Such increases, in and of themselves, suggest that as the magnitude of the ITD increases, the ability to compensate it decreases. The validity of that interpretation rests on the fact that thresholds obtained in the (No)±τ(Sπ)τ, double-delay configuration, for which the listener cannot internally compensation the

ITD, fell above their (NoSπ)τ counterparts at each and every non-zero ITD. These outcomes provide further evidence that listeners do, indeed, internally compensate external ITDs for stimuli presented in the (NoSπ)τ configuration and do so in a manner that is less and less precise as external ITD is increased.

Figure 3 contains (NoSπ)τ average thresholds replotted after taking into account listeners' hearing levels at 4 kHz and listeners' ages, respectively. Beginning with the left-hand upper and lower panels, the dotted and dash-dotted lines plot the respective mean detection thresholds for the data partitioned by hearing level. The grand mean across all 31 listeners (see Fig. 2) is represented in each panel by the heavy solid line.

We also partitioned the data by age (>45 yr or <=45 yr). Those partitioned data are represented in Fig. 3 by the half-filled symbols with mean thresholds from listeners aged >45 yr represented by the symbols with their top halves filled and mean thresholds from listeners aged <= 45 yr represented by symbols with their bottom halves filled. Note that, for the data obtained both at the CF of 4 kHz (top-left panel) and the CF of 500 Hz (bottom-left panel), in almost all cases*:* 1) the binaural detection thresholds for listeners having hearing thresholds >7.5 dB HL *fall above the grand mean regardless of age*; 2) the binaural detection thresholds for listeners having hearing thresholds <= 7.5 dB HL *fall below the grand mean regardless of age*.

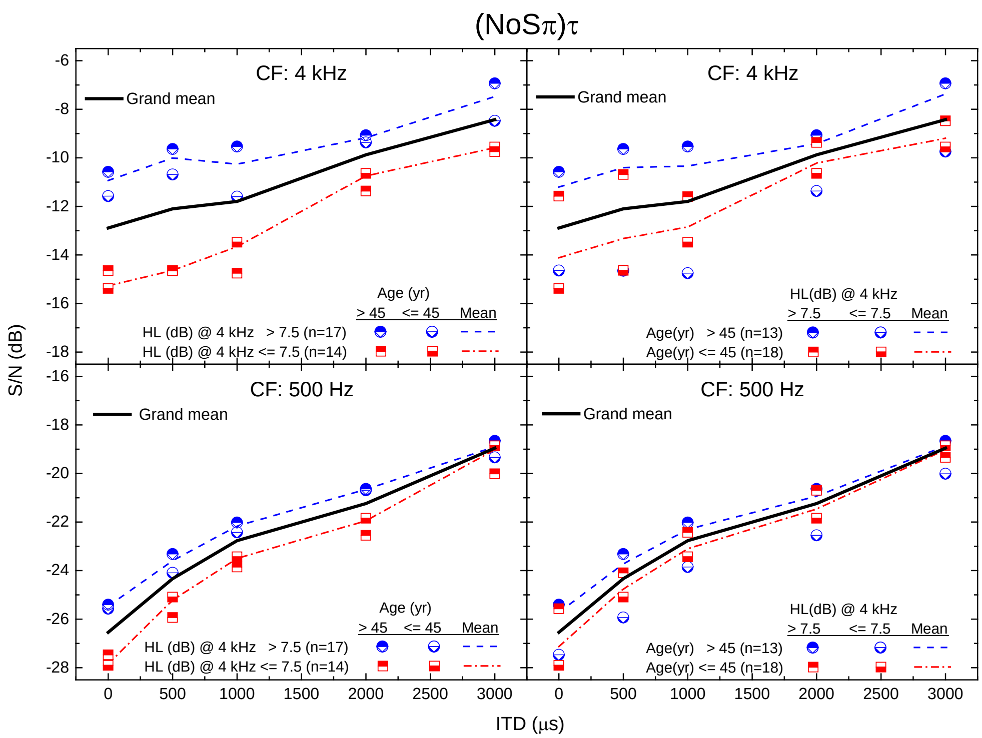

Fig. 3

Now, consider the right-hand panels of Fig. 3. In these cases, the data were first partitioned by age and then further partitioned by hearing threshold (<=7.5 or >7.5 dB HL). The repartitioned data are shown by the half-filled symbols with the mean thresholds obtained from listeners having HLs @ 4 kHz > 7.5 dB represented by the symbols with their top-halves filled and the mean thresholds obtained from listeners having HLs @ 4 kHz <= 7.5 dB represented by symbols with their bottom-halves filled.

Note that the half-filled circles and half-filled squares are neither consistently separated from each other nor clustered around their respective means, as was the case for the repartitioned data in the left-hand panels. More specifically, the fact that the half-filled squares and circles are scattered above and below the grand mean demonstrates ***that age in and of itself is not determinative of relative sensitivity to ITD.*** In sum, the data in Fig. 3, obtained from a sample of 31 listeners, support the proposition that differences in the precision of ITD-coding are more likely attributable to differences in hearing threshold than to differences in age.

The data in the left-hand panel of Fig. 3 are replotted in Fig. 4. The dotted lines in represent predictions based on computational techniques adapted from van der Heijden and Trahiotis (1999). For the (NoSπ)τ condition, it was assumed that "noisy" compensating internal delays are employed by the listener and that those internal delays are implemented with less and less precision as their magnitudes are increased. The predictions, which account on average for 96% of the variance in the behavioral data, bolster the interpretation that listeners having "slight" hearing loss can be characterized as having diminished precision of ITD-coding, with greater losses of such precision occurring for smaller (nearer to "midline") values of ITD.

The totality of the data and the theoretical accounting of them permit two general conclusions: First, hearing-losses, even when slight, can adversely affect temporal-coding-based binaural detection in the spectral region of the loss without affecting energy/level-based monaural detection for the same stimuli. Second, the losses of precision of ITD-coding measured in our study, appear to support the proposition that differences in the precision of ITD-coding are more attributable to differences in hearing level than to (correlated) differences in age.

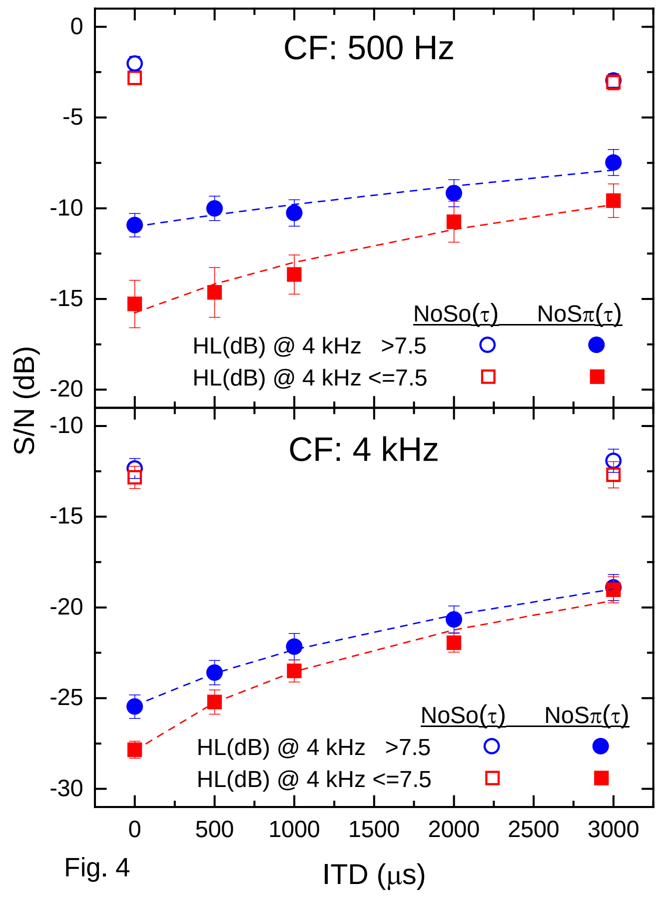

Fig. 4

We presented our results at two meetings drawing international attendance. The first was the *Binaural and Spatial Hearing (BASH)* meeting held at Boston University (October, 2015). There, we reported measurements of precision of ITD-coding and showed how our quantitative modeling to describe them could also be applied to related recent and classic binaural detection data. The second was the *Midwinter Meeting of the Association for Research in Otololaryngology* (Februrary, 2016). There, we presented empirical data and quantitative analyses *suggesting that even "slight" hearing losses can lead to degradations in binaural ITD-processing*. The presentation drew substantial interest and was quite well received. We submitted a manuscript to the *Journal of the Acoustical Society of America* reporting an expanded set of those findings.

IV. Period 1: 15-June-2016 – 14-June-2017

a. Results Dissemination

The results have been disseminated via publications in journals including the *Journal of the Acoustical Society of America* and via presentations at national/international meetings.

<u>Publications:</u>

Bernstein, L. R., and Trahiotis, C. (2016). "Behavioral manifestations of audiometrically-defined "slight" or "hidden" hearing loss revealed by measures of binaural detection," J. Acoust. Soc. Am. 140, 3540-3548.

Bernstein, L. R., and Trahiotis, C. (2017). “An interaural-correlation-based approach that accounts for a wide variety of binaural detection data,” J. Acoust. Soc. Am. 141, 1150-1160.

Presentations:

Bernstein, L. R., and Trahiotis, C. (2016). “Audiometrically-defined ‘slight’ or ‘hidden’ hearing losses can be manifested as changes in binaural detection, J. Acoust. Soc. Am. 140, 3100. (Meeting of the Acoustical Society of America, December, 2016)

Bernstein, L. R. and Trahiotis, C. (2016). "A new cross-correlation-based approach accounts for a wide variety of binaural detection data," Binaural BASH, Boston University.

Bernstein, L. R. and Trahiotis, C. (2017). “A new approach that accounts for several ‘problematic’ sets of binaural detection data obtained with narrow-band, partially interaurally correlated maskers,” Abstracts of the Fortieth Midwinter Research Meeting.

b. Accomplishments/Progress

i. Results concerning behavioral manifestations of slight and/or hidden hearing loss

Empirical and theoretical findings

As described earlier, the experiments conducted utilized a novel set of stimulus configurations to measure binaural signal detection. Data obtained reveal how precision of ITD-coding changes as a function of both reference ITD and center frequency.

Consistent with one of our goals, our findings concerning ***behaviorally-measured binaural deficits associated with slight and/or hidden hearing loss*** were published in the *Journal of the Acoustical Society of America*. The results of that study were described under “accomplishments” for the previous reporting period. Those results suggest that: 1) hearing-losses, even when slight, can adversely affect temporal-coding-based binaural detection in the spectral region of the loss without affecting energy/level-based monaural detection for the same stimuli; 2) the observed losses of precision of ITD-coding appear to support the proposition that differences in the precision of ITD-coding are more attributable to differences in hearing level than to (correlated) differences in age.

Subsequent to the publication of those results, our novel findings were reported by the lay press as well as in summaries authored by and for professional organizations. To our knowledge, those findings represented the first behavioral evidence for auditory deficits resulting from slight and/or “hidden” hearing loss.

A cross-correlation-based model of binaural hearing

As mentioned above, a *stimulus-based* computational model provided a highly successful account of our behavioral data. That success notwithstanding, as we have demonstrated and argued in several of our previous publications, comprehensive, generalizable explanations of binaural processing can be achieved only when one considers the stimuli *as processed by the auditory system*. Therefore, we considered it essential to account for the data we collected, and for sets of data we planned to collect, via our cross-correlation-based model of binaural processing that includes known stages of peripheral auditory processing.

Interaural cross-correlation-based models of binaural processing have accounted successfully for a wide variety of binaural phenomena including binaural detection, binaural discrimination, and measures of extents of laterality based on interaural temporal disparities (ITDs), interaural intensitive disparities (IIDs), and their combination. Still, there remained stimulus contexts for which commonly used correlation-based approaches failed to provide adequate explanations of binaural detection data. One such context was the binaural detection of signals masked by certain noises that are narrow-band

and/or interaurally partially correlated. Because the experiments described above fall squarely within that context, we sought to develop a general and straightforward cross-correlation approach that would account successfully for, not only our new data, but for a wide variety of "problematic" binaural detection data collected from various laboratories over the past 50 years or so. Our goal was to account for the data via a model that 1) incorporated the same stages of peripheral and central auditory processing that we successfully used in the past and 2) to do so without employing ad hoc parameters and assumptions.

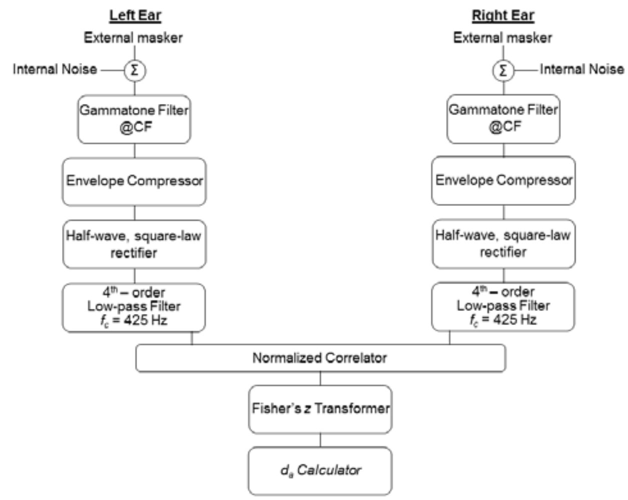

Fig. 2

We were highly successful and our results were published in the *Journal of the Acoustical Society of America*. In that publication, we demonstrated that a cross-correlation-based model that includes stages of peripheral auditory processing (see Fig. 2) can, *when coupled with an appropriate decision variable*, account well for a wide variety of classic and recently published binaural detection data including those that have, heretofore, proven to be problematic. The novel "twist" was to employ a decision variable, referred to as d_a, that takes into account *both the mean and the variance* of the estimates of the interaural cross-correlation computed upon the stimuli as processed by the auditory periphery. That strategy is consistent with classical signal-detection theory. Across 18 panels of data reported in six separate studies that were conducted between 1965 and 2015 the amounts of variance accounted for by the model had a median value of 94%! Such predictive accuracy attests to the model's predictive validity and generality.

This success left us well-positioned to fulfil our goal of explaining and accounting for our behavioral data. Of particular interest was the ability of the model ***to suggest which aspects of auditory processing likely account for the deficits in binaural processing that appear to accompany slight and/or hidden hearing loss.***

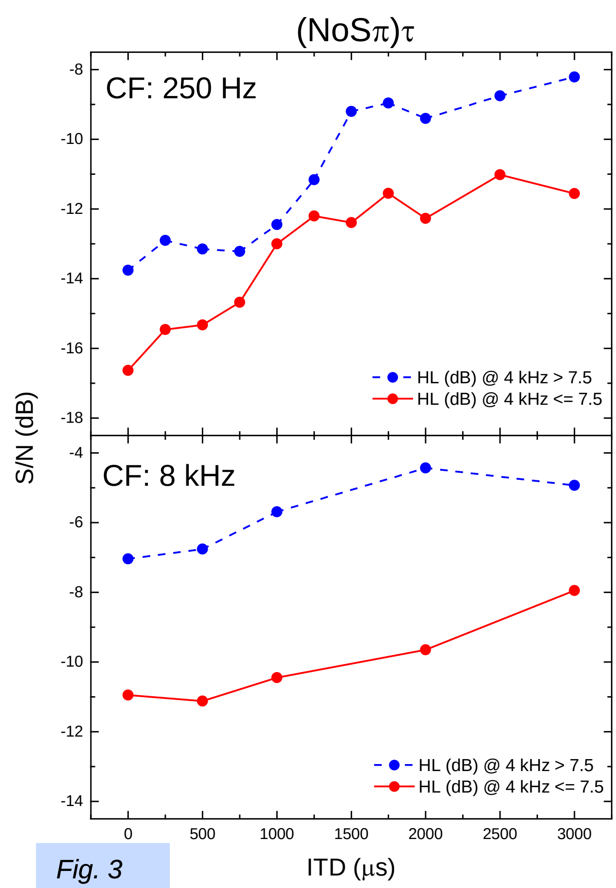

Fig. 3

<u>Analysis of data obtained concerning binaural precision across center frequency</u>

Measures neared completion and analysis began for the experiment designed to assess precision of binaural processing for center frequencies over the range 125 Hz to 8 kHz. Detection thresholds using our novel stimulus configurations were measured for a group of human listeners aged between about 25 and 60 years and all having audiometric thresholds no greater than those characterized as “slight loss.”

Fig. 3 shows preliminary results obtained during the reporting period. The figure is similar to Fig. 1 in that detection thresholds obtained using the (NoSπ)τ configuration are plotted as a function of the interaural delay (τ). For center frequencies of 250 Hz and 8 kHz, thresholds obtained from listeners having HLs @ 4 kHz > 7.5 dB are uniformly higher than corresponding thresholds obtained from listeners having HLs @ 4 kHz <= 7.5 dB. These results suggest that binaural processing deficits extend over a broad range of frequencies for listeners exhibiting slight and/or hidden hearing losses. The next step was to apply the quantitative model (see Fig. 2) to help determine the factors underlying those deficits.

V. Period 1: 15-June-2017 – 14-June-2018

a. Results Dissemination

The results have been disseminated via publications in journals including the *Journal of the Acoustical Society of America* and via presentations at national/international meetings.

<u>Publications:</u>

Bernstein, L. R., and Trahiotis, C. (2018). “A binaural detection task that reveals deficits in listeners having ‘slight’ or ‘hidden’ hearing loss,” ENT & Audiology News, 27(1), 78-79.

Bernstein, L. R., and Trahiotis, C. (2018). “Effects of interaural delay, center frequency, and no more than ‘slight’ hearing loss on precision of binaural processing: Empirical data and quantitative modeling,” J. Acoust. Soc. Am., under review.

<u>Presentations:</u>

Bernstein, L. R. and Trahiotis, C. (2018). “Effects of magnitude of interaural delay, center frequency, and hearing status on precision of binaural processing: Empirical data and quantitative modeling,” Abstracts of the Forty-First Midwinter Research Meeting.

Bernstein, L. R., and Trahiotis, C. (2017). “Binaural detection-based estimates of precision of coding of interaural temporal disparities across center frequency,” J. Acoust. Soc. Am. 141, 3973 (Meeting of the Acoustical Society of America, June, 2017)

Bernstein, L. R. and Trahiotis, C. (2017). "Binaural detection and the delay line: The best place to look–period!," Binaural BASH, Boston University.

b. Accomplishments/Progress

i. Results concerning behavioral manifestations of slight and/or hidden hearing loss

<u>Empirical and theoretical findings</u>

Our first, large-scale study (Bernstein and Trahiotis, 2016) used the paradigm described above to characterize precision of ITD coding in listeners having normal audiometric thresholds and audiometric thresholds characterized by, at most, “slight hearing loss.” The results of that study revealed ***behaviorally-measured binaural deficits associated with slight and/or hidden hearing loss.*** To our knowledge, this was the first demonstration of such a behaviorally measured auditory deficit in listeners whose audiograms would be considered to be unremarkable clinically. Overall, the results of that study suggest that: 1) hearing losses, even when slight, can adversely affect temporal-coding-based binaural detection in the spectral region of the loss without affecting energy/level-based monaural detection for the same stimuli; 2) the observed losses of precision of ITD-coding appear to support the proposition that differences in the precision of ITD-coding are more attributable to differences in hearing level than to (correlated) differences in age.

Our 2016 study was conducted with stimuli centered at either 500 Hz (a low frequency) or at 4 kHz (a high frequency). During this reporting period, we completed our second large study, which was designed to investigate how precision of binaural processing is affected by magnitude of ITD, and the hearing status of the listener *across a broad range of frequencies*. There were two important reasons to extend our observations in this manner. First, it allowed us to determine whether and to what degree the ***binaural deficits associated with slight and/or hidden hearing loss*** observed in the 2016 study are manifest over a broad range of the spectrum. Second, it provided the comprehensive, parametric set of data required to evaluate our cross-correlation-based model of binaural processing that includes known stages of peripheral auditory processing. Details of that model were published in 2017. As we have argued in our prior publications, comprehensive, generalizable explanations of binaural processing can be achieved only when one considers the stimuli *as processed by the auditory system*. A major goal of this endeavor was to use the quantitative model to gain insight regarding ***why*** listeners with slight and/or hidden hearing loss perform poorer on our binaural detection tasks.

Signal detection thresholds were measured using 100-Hz-wide Gaussian noise maskers and tonal signals centered at octave frequencies spanning the range from 250 Hz to 8 kHz. The lowest three center frequencies fell within spectral regions within which the fine-structures of the stimulus waveforms convey the interaural temporal information; the highest three center frequencies fell within spectral regions within which the envelopes of the stimulus waveforms convey the interaural temporal information. Because binaural detection advantages are known to be relatively small for high-frequency signals and Gaussian noise maskers, we also employed transposed stimuli at center frequencies of 2, 4, and 8 kHz. The transposed stimuli were constructed and presented as follows. For observation intervals containing the signal (S+N), a 125-Hz tonal signal was added to a 125-Hz-centered, 100-Hz-wide narrowband Gaussian noise at the appropriate signal-to-noise ratio and then the entire waveform was transposed to 2, 4, or 8 kHz. For observation intervals containing only the masker, the waveforms were created by transposing only the 125-Hz-centered masker (N) to the desired center frequency. Seven human listeners aged between about 25 and 60 years were employed. All had audiometric thresholds no greater than those characterized as “slight loss.”

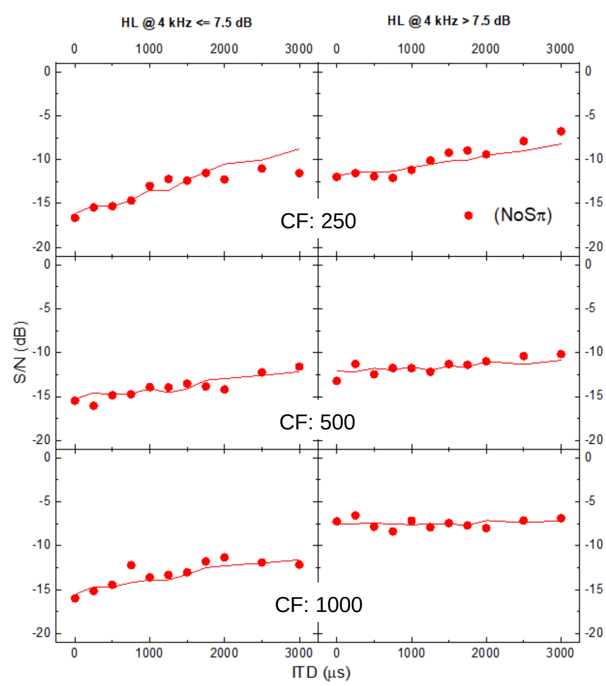

Fig. 1

The circles in each panel of Figure 1 represent mean threshold S/N (dB) obtained in the $(NoS\pi)\tau$ configuration, plotted as a function of ongoing ITD. The solid lines represent predictions from our cross-correlation-based model Descriptions of the interaural cross-correlation based model and how it was employed to generate the predictions are presented in the next section.

The upper, middle, and lower panels present data obtained at center frequencies of 250, 500, and 1000 Hz, respectively. The three left-hand panels represent the average of the thresholds obtained from the four listeners whose audiometric thresholds at 4 kHz were <= 7.5 dB

HL; the three right-hand panels represent the average of the thresholds obtained from the three listeners whose audiometric thresholds at 4 kHz were > 7.5 dB HL. For listeners having hearing thresholds at 4 kHz <= 7.5 dB HL, detection thresholds were similar across center frequency, ranging from about -15 dB when the ITD was zero to -11 dB or so when the ITD was 3000 µs. In contrast, ***for listeners having hearing thresholds at 4 kHz >7.5 dB HL, thresholds were somewhat higher than those obtained from the other group at all values of ITD tested and the relations between thresholds and ITD differed depending on center frequency.*** When the center frequency was 250 Hz (upper right panel), thresholds increased by about 5 dB as ITD was increased from 0 to 3000 µs. When the center frequency was 500 Hz or 1000 Hz, thresholds were remarkably constant all values of ITD. The largest departure between the performances of the two groups occurred at a center frequency of 1000 Hz.

Figures 2 and 3 display the thresholds obtained at center frequencies of 2000, 4000, and 8000 Hz for the Gaussian noise and transposed stimuli, respectively. Recall that these are frequencies for which the envelope of the stimulus conveys the binaural information. ***Notably, for both types of stimuli, the thresholds obtained from the "> 7.5 dB" group are, at all three center frequencies, elevated as compared to the corresponding thresholds obtained from the "<= 7.5 dB" group.*** Interestingly, the slopes of the functions relating threshold to ITD in Fig. 2 are relatively shallow compared to those observed in Figs. 1 and 3.

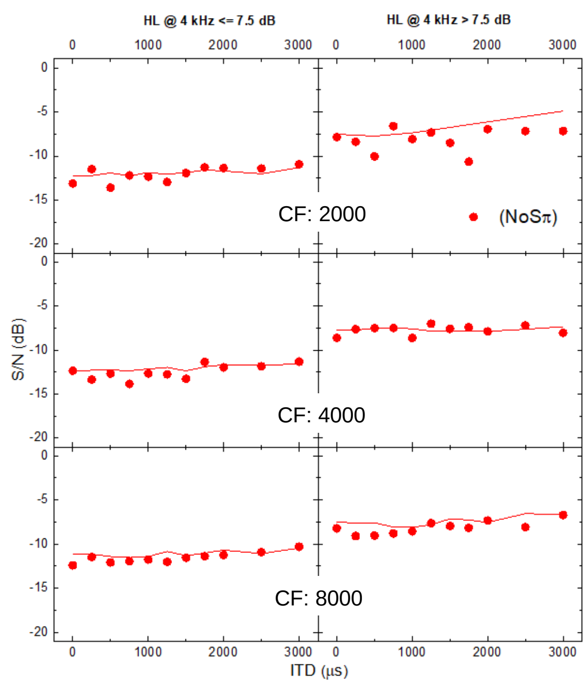

Fig. 2

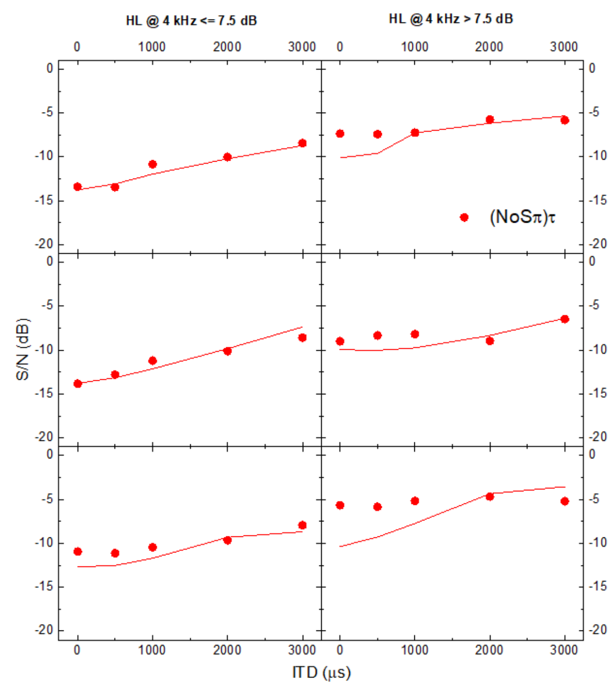

Fig. 3

The solid lines in Figs. 1-3 indicate that, across center frequency and type of stimulus, the data appear to be captured quite well by our quantitative model. In fact, the average rms error between the obtained data and the predictions of the model across all six center frequencies and the two groups of listeners was found to be ***only 1.0 dB***.

II. Quantitative Modeling of the Data

As we have demonstrated and argued in several of our publications, comprehensive, generalizable explanations of binaural processing can be achieved only when one considers the stimuli *as processed by the auditory system*. Therefore, we considered it essential to account for the data we collected via our cross-correlation-based model of binaural processing that includes known stages of peripheral auditory processing. A major goal of this endeavor was, as stated above, to use the quantitative model to gain insight regarding ***why listeners with slight and/or hidden hearing loss perform poorer on our binaural detection tasks.***

A block diagram of our model is shown in Fig. 3. As we described in Bernstein and Trahiotis (2017), the model employs a decision variable, referred to as d_a, that takes into account *both the mean and the variance* of the estimates of the interaural cross-correlation computed upon the stimuli as processed by the auditory periphery. That strategy is consistent with classical signal-detection theory. Briefly, the same stimuli as those used in our experiments served as inputs to the model. The process allowed us to relate the decision variable of the model, d_a, to detection thresholds in S/N (dB).

As shown in Fig. 4, the model incorporates two sources of internal, or neural processing noise that serve to limit performance. Those sources of noise are marked by the dark red arrows in the diagram. The first type of internal noise (near the top of the diagram) is a stimulus dependent, additive, interaurally uncorrelated noise. That type of internal noise been validated in many studies of binaural and monaural detection conducted over decades. The second type of internal noise is one that is assumed to arise along the internal delay-line within the binaural processor. The magnitude of that noise is one that increases with the magnitude of the ITD being processed.

The model was used to account for the data separately for each group of listeners and separately at each center frequency tested. For all of the binaural detection conditions (including a control condition not shown) we determined: 1) the values of the decision variable, d_a; 2) the level of the stimulus-dependent additive internal noise; 3) the rate of growth of delay-line noise (referred to as α) yielding the best fits between predicted and obtained thresholds.

Table 1

		Group	
		HL @ 4 kHz <= 7.5 dB	HL @ 4 kHz > 7.5 dB
		d_a = 2.35	d_a = 2.30
250 Hz	Internal Noise Level (dB re external masker)	-11	-7
	α	0.65	0.65
500 Hz	Internal Noise Level (dB re external masker)	-11	-8
	α	0.50	0.50
1000 Hz	Internal Noise Level (dB re external masker)	-12	-4
	α	0.45	0.40
2000 Hz (Gaussian & Transposed	Internal Noise Level (dB re external masker)	-11	-7
	α	0.75	0.85
4000 Hz (Gaussian & Transposed	Internal Noise Level (dB re external masker)	-11	-7
	α	0.75	0.75
8000 Hz (Gaussian & Transposed	Internal Noise Level (dB re external masker)	-10	-7
	α	0.75	0.85

Fig. 4

Table 1 shows, for each of the two groups of listeners, the best-fitting values of d_a (sensitivity to changes in interaural correlation) and, for each center frequency, the levels of the internal noise relative to the external noise masker, and growth of noise along the delay-line (α). The best fitting values of d_a for the two groups (2.35 and 2.30, respectively) are functionally identical. It, therefore, appears that both groups of listeners based their decisions on changes in interaural correlation of the stimuli, *as processed*, and that the two groups were *equally sensitive* to changes in interaural correlation. Equal sensitivity at the "central" decision stage is consistent with the inference that the empirical differences in detection thresholds found between the two groups of listeners reflect how precisely the stimuli were processed *prior* to the computation of the decision statistic. ***In this view, the elevations in thresholds (poorer performance) required by the > 7.5 dB group reflect compensatory increases in external signal-level required for them to overcome less precise processing in order to achieve their criterion*** d_a ***of 2.30***.

Now, what accounts for such less precise processing for the > 7.5 dB group? Table 1 indicates that it is the level of interaurally uncorrelated internal noise. The table shows that, overall, the level of that internal noise is about -7 dB, for the > 7.5 dB group. ***That level is 4 dB higher than the level of about -11 dB found for the <= 7.5 dB group.***

Perhaps as important, Table 1 also shows that the differences in binaural thresholds found between the two groups *cannot be accounted for* in terms of α (growth of delay-line noise). Note that, the values of α for the two groups are quite similar across all center frequencies, being somewhat higher for the higher center frequencies.

Third, and finally, ***to the extent that the experiments themselves and their quantitative analysis via the model can be generalized, it appears that the degradations of binaural processing accompanying slight and/or "hidden" loss stem principally (if not, solely) from "noisy" monaural inputs to a binaural comparator.*** Perforce, they do not appear to stem from central factors such as additional noise within the binaural comparator (i.e., delay-line noise) or within the decision-making process, *per se*.

Thus, our quantitative model not only accounts very well for the data overall, it appears to suggest a direct answer to ***why*** listeners with slight and/or hidden hearing loss perform poorer on our binaural detection tasks.

Consistent with our goals, a manuscript reporting the results described above was submitted to the *Journal of the Acoustical Society of America*.

VI. Period 1: 15-June-2018 – 23-January-2019

a. Results Dissemination

<u>Publications:</u>

Bernstein, L. ., and Trahiotis, C. (2018). "Effects of interaural delay, center frequency, and no more than 'slight' hearing loss on precision of binaural processing: Empirical data and quantitative modeling." J. Acoust. Soc. Am. 144, 292-307.

Bernstein, L. R., and Trahiotis, C. (2019). "No more than 'slight' hearing loss and degradations in binaural processing," J. Acoust. Soc. Am. 145, 2094-2102.

<u>Presentations:</u>

Bernstein, L. R., and Trahiotis, C. (2019). "Accounting for a wide variety of binaural detection data by combining cross-correlation and signal-detection theory approaches," J. Acoust. Soc. Am. 145, 1684.

Bernstein, L. R. and Trahiotis, C. (2019). “Listeners with no more than “slight” hearing loss who exhibit deficits in binaural detection also exhibit deficits in the ability to discriminate changes in interaural time and interaural intensity,” Abstracts of the Forty-Second Midwinter Research Meeting.

Bernstein, L. R., and Trahiotis, C. (2018). “Effects of interaural delay, center frequency, and no more than ”slight” hearing loss on binaural processing: Behavioral data and quantitative analyses,” J. Acoust. Soc. Am. 144, 1710.

Bernstein, L. R. and Trahiotis, C. (2018). “A cross-correlation-based model incorporating internal noise explains effects of hearing status on binaural signal detection, ITD-discrimination, and IID-discrimination,” Binaural Bash, Boston University.

b. Accomplishments/Progress

i. Extending both the generality of our findings re binaural deficits and our quantitative modeling

An additional study was begun under the auspices of Award No. N00014-15-1-2140 and completed shortly after its formal ending. One goal of the study was to determine whether listeners classified as having, at most, slight hearing loss would also exhibit deficits in binaural tasks requiring the discrimination of interaural temporal disparities (ITDs) or interaural intensive disparities (IIDs). We hypothesized that they would because signal-dependent changes in ITD and IID are the underlying physical cues known to foster binaural signal detection. A second goal was to determine whether any such deficits would be quantitatively accounted for by the same type of interaural cross-correlation based model that successfully accounted for binaural detection. If the model were found to be successful, then that finding would attest to its generality.

In order to fulfil both goals, we 1) measured binaural detection at center frequencies of 500 Hz and 4 kHz, where the interaural cues are conveyed by the fine-structures and envelopes of the waveforms, respectively; 2) measured threshold-ITDs and threshold-IIDs at the same two center frequencies; 3) made predictions via the model of threshold-ITDs and threshold-IIDs after suitably modifying the form of the model’s decision variable. We used the thresholds of binaural detection in order to estimate the levels of peripheral, stimulus-dependent, additive internal noise and then used those levels of internal noise in order to make quantitative predictions of threshold-ITDs and threshold-IIDs. Eighteen listeners participated.

Detection thresholds, indicated as S/N in dB, are shown separately in Fig. 1 for the stimuli centered at 500 Hz (upper panel) and 4 kHz (lower panel). The thresholds within each panel are partitioned both by stimulus configuration (NoSo or NoSπ) and by group hearing-level at 4 kHz (either <= 7.5 dB HL or > 7.5 dB HL). The thresholds depicted are means calculated across the 10 listeners in the “<= 7.5 dB group” and the eight listeners in the “> 7.5 dB group.” Error bars represent one standard error of their respective means.

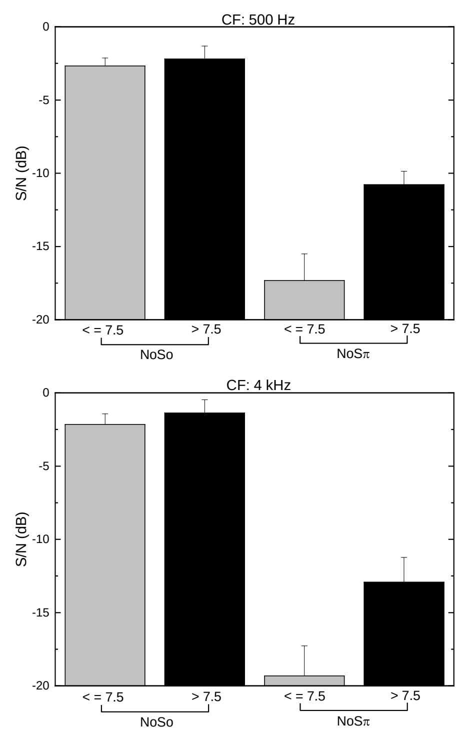

Figure 1

For both center frequencies, NoSo thresholds, which represent “monaural” processing are essentially the same (and not statistically different) across both groups of listeners while NoSπ thresholds are elevated by about 6 dB for the > 7.5 dB group as compared to the <= 7.5 dB group. Statistical tests confirmed those observations. These outcomes, revealing statistically significant elevations of binaural detection thresholds for listeners with no more than slight hearing loss, replicate results published earlier in Bernstein and Trahiotis (2016; 2018). Note that partitioning the listeners by age, rather than hearing status, yielded no significant differences across any of the comparisons.

Discrimination thresholds for ITD (left-hand ordinate) and IID (right-hand ordinate) are shown separately in Fig. 2. The asterisks represent predictions of our quantitative model, and are discussed below. Confirming our hypothesis, listeners in the > 7.5 dB group exhibit substantial and statistically significant elevations in both ITD- and IID-thresholds and do so at each of the two center frequencies. In all four cases, discrimination thresholds obtained from the >7.5 dB group (who would be classified, audiometrically, as having no more than slight loss) are elevated, on average, by a factor of about 1.7. Once again, partitioning the listeners on the basis of age revealed no significant differences between the two groups for ITD- or IID-thresholds at either center frequency. Thus, neither the degradations in binaural detection nor the degradations in binaural discrimination observed with our > 7.5 dB group appear to be attributable to age.

III. Quantitative Analyses

The primary goal of our quantitative analyses was to determine whether the elevations in ITD- and IID-thresholds exhibited by the > 7.5 dB group in this study could be accounted for by the same type of interaural cross-correlation based model that successfully accounted for elevations in binaural *detection* thresholds in similar listeners in our previous study (Bernstein and Trahiotis, 2018). In order to do so, we began by applying that model to the binaural detection data obtained in this study. Specifically, we used that model to estimate, separately for each of the two groups of listeners in this study, the levels of stimulus-dependent, additive internal noise required to account for their detection thresholds. Then, we used those estimates of additive internal noise to make predictions of ITD- and IID-thresholds. In order to accomplish the latter, we modified the model so that its decision variable was based on distributions of samples of internal interaural lateral “position,” rather than on distributions of samples of internal interaural correlation (more properly, coherence) like those used in our previous study to predict binaural detection thresholds.

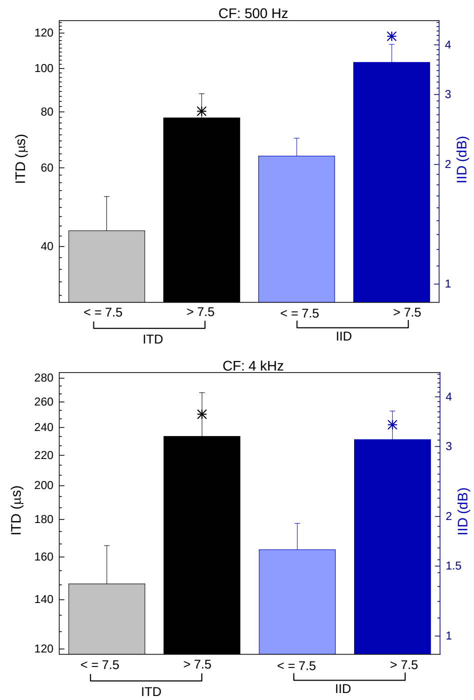

Figure 2

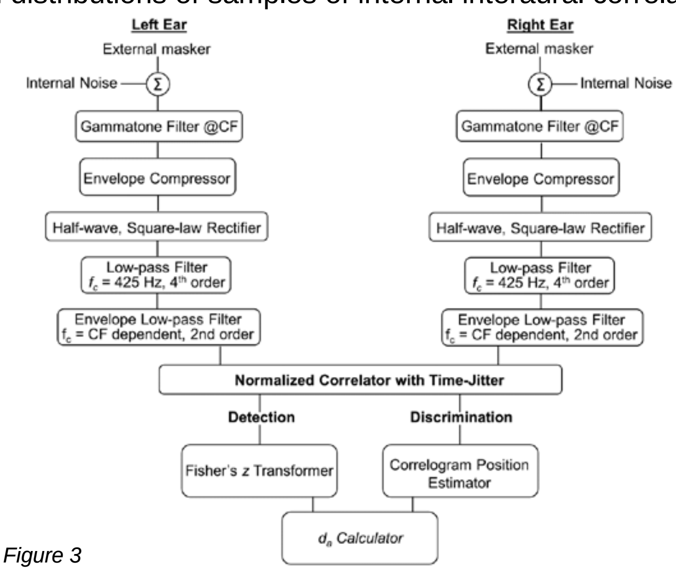

Figure 3

A block diagram of the model is shown in Fig. 3. As shown, the model incorporates the two sources of internal, or neural processing noise that serve to limit performance and which were discussed above. The first type of internal noise (near the top of the diagram) is a stimulus dependent, additive, interaurally uncorrelated noise. That type of internal noise been validated in many studies of binaural and monaural detection conducted over decades. The second type of internal noise is one that is assumed to arise along the internal delay-line within the binaural processor. The magnitude of that noise is one that increases with the magnitude of the ITD being processed.

In order to estimate the levels of internal noise affecting performance for the two groups of listeners, we capitalized on the procedures and computations reported in (Bernstein and Trahiotis, 2018). In that publication, we described how the model was used to derive functions relating (S/N) to d_a for a variety of signal-plus-masker waveforms while employing a wide range of levels of stimulus-dependent, additive internal noise crossed with a wide range of values of exponentially increasing time-jitter (indexed as α) along the putative internal delay-line. The stimuli for which those functions were derived included the actual stimuli used in the detection experiments.

In our previous study, we found that the best predictions of threshold were obtained when d_a was equal to 2.35 and when α was 0.5 at 500Hz and 0.75 at 4 kHz. Using those values of d_a and α in conjunction with the derived functions relating (S/N) to d_a, allowed us to determine which levels of internal noise led to the best estimates of the detection thresholds obtained from each of the two groups of listeners shown in Fig. 1. For the center frequency of 500 Hz, those levels were found to be -15 and -9 dB, respectively, for the <= 7.5 dB and > 7.5 dB groups. For the center frequency of 4 kHz, those levels were found to be -14 and -8 dB, respectively, for the <= 7.5 dB and > 7.5 dB groups. Consistent with our previous findings, the level of internal noise derived for > 7.5 dB was higher than that derived for the <= 7.5 dB group. That is, higher levels of internal noise were associated with slight hearing loss.

In order to make predictions of ITD- and IID-thresholds, we used the values of the model parameters described above along with the levels of internal noise derived for each group from the detection data (Fig. 1) in order to derive functions relating ITD to d_a and functions relating IID to d_a for the stimuli employed in the discrimination experiments that yielded the data shown in Fig. 2.

Figure 4 illustrates, in general and using an arbitrary abscissa, how we used the information described above to make predictions of ITD- and IID-thresholds for the > 7.5 dB group. The first step was to plot derived functions relating d_a to the magnitude of the interaural cue assuming each group's derived level of internal noise. The second step was to determine the value of d_a corresponding to the threshold obtained from the <= 7.5 dB group. In our example, the value of d_a is 1.0. Next, assuming that both groups of listeners had *that same* underlying value of d_a, the predicted threshold for the > 7.5 dB group was taken to be the value of interaural cue that intersected their function at the same value of d_a (in our illustration, 1.0). The predictions of threshold derived from those functions using the scheme described above are indicated as asterisks in Fig. 2. Note that the predictions are quite accurate in terms of predicting the differences found between the two groups across both types of discrimination tasks and across low and high center frequencies.

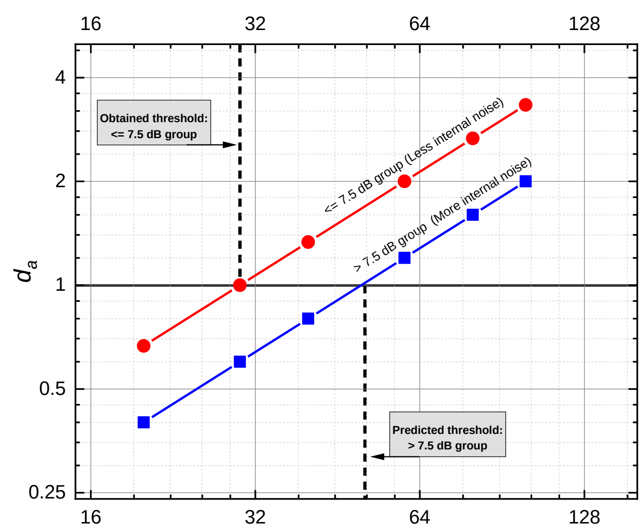

Figure 4

The results reported above demonstrate that listeners classified as having, at most, slight hearing loss and who exhibit deficits in binaural detection tasks, also exhibit deficits in tasks requiring the discrimination of ITDs and IIDs. As discussed above, we hypothesized that would be the case because signal-dependent changes in ITD and IID are the underlying physical that foster binaural signal detection.

The results of our quantitative analyses demonstrate that the same quantitative, cross-correlation-based model that successfully accounted for elevations in binaural detection thresholds among such listeners (Bernstein and Trahiotis, 2018) also accounted for their elevated ITD- and IID-thresholds, so long as the decision variable at the output of the model was appropriate for the task at hand. These outcomes attest to the generality of our modelling approach and lend support to the notion that differences in binaural performance observed across our two groups, be they in binaural detection or binaural discrimination tasks, arise from increased levels of peripherally-based internal noise for listeners who exhibit slight (and clinically negligible) elevations in audiometric thresholds.

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14. ABSTRACT
Our systematic program of research showed that 1) hearing losses, even when slight and/or clinically negligible, can adversely affect binaural (two-eared) processing and 2) the observed losses of precision of ITD-coding appear to support the proposition that differences in the precision of ITD-coding are more attributable to differences in hearing level than to (correlated) differences in age. Quantitative modeling revealed that that the degradations of binaural processing accompanying slight and/or "hidden" loss stem principally (if not, solely) from "noisy" monaural neural inputs to a binaural comparator.

15. SUBJECT TERMS
Hidden hearing loss, binaural processing, situational awareness, localization of sound

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