Temporal Damping in Response to Broadband Noise. II. Auditory Nerve

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INTRODUCTION

Interaural time differences (ITDs) are temporal delays between the sound waveforms at the two ears and constitute a major cue to localize sounds in space. The firing rate of low-frequency neurons in the inferior colliculus (IC) show a damped oscillatory response as a function of interaural time differences (ITDs) of broadband noise. It was previously shown that several features of such noise-delay functions are well predicted by the composite curve, generated by the linear summation of responses to tones with varying ITD. This indicates a surprising degree of linearity at the midbrain level of the auditory pathway. A similar comparison between responses to tones and to noise has not been made at a more peripheral, monaural level and it is therefore unclear to what extent this linearity reflects peripheral physiology. Here, we compare cat auditory nerve responses to broadband noise and to isolevel tones. We constructed shuffled autocorrelograms for responses to tones and summed across frequencies to obtain a monaural composite curve. We then compare this composite curve to the shuffled autocorrelogram of responses to broadband noise and find that the match between tonal and noise responses is poorer at the level of the auditory nerve than at the level of the IC. The apparent linearity of responses in the IC is thus even more surprising than was apparent from its original report because it results from mechanisms interposed between the auditory nerve and the IC.

METHODS

Recording

Our methods for single-unit recording in the AN have been described before (Louage et al. 2004). All procedures were approved by the K.U. Leuven Ethics Committee for Animal Experiments and were in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals. AN data were obtained from four cats. Anesthesia was induced with a 1:3 mixture of acepromazine:ketamine and maintained with pentobarbital for surgical preparation and recording. The animals were placed on a heating pad in a double-walled sound-attenuated chamber (IAC, Niederkürtchen, Germany). The bulla was vented with a polyethylene tube. The AN was exposed through a posterior fossa approach, involving removal of a meniscus. There are two reasons that we want to compare peripheral and midbrain responses quantitatively. First, it is unclear how remarkable the linear behavior of binaural IC neurons is: a comparison of temporal responses to tones and noise has not been made for peripheral neurons as it has for the IC. If similar analyses are performed, does the apparent linearity of binaural responses in the IC perhaps also apply to the monaural level? Second, in a previous study (Joris et al. 2005) we found that ND functions of IC neurons differ over a fourfold range in their damping i.e., in the decay of these functions with ITD. Some ND functions are very oscillatory, whereas others are very damped, even among neurons of similar characteristic frequency (CF: frequency of lowest threshold). This is unexpected from a monaural, peripheral viewpoint. The peripheral neurons that provide input to the binaural system are rather stereotyped in their tuning properties and a coincidence-type binaural mechanism would be expected to generate rather stereotyped ND functions. More specifically, if peripheral neurons are stereotyped in terms of the bandwidth of their frequency tuning, they would be expected to generate ND functions with stereotyped damping. Monaural neurons with restricted spectral bandwidth are expected to generate weakly damped ND functions; neurons with wider spectral bandwidth should generate more strongly damped ND functions.

We obtained auditory-nerve (AN) responses to stimuli that are typically used in binaural experiments and used a coincidence or autocorrelation analysis to compare monaural responses with binaural responses reported in a preceding paper (Joris et al. 2005). Our two main findings are 1) that the match between broadband and tonal responses is actually worse at the peripheral level than that at the central level and 2) that damping in responses to noise strongly differs between the peripheral and central levels.

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small area of cerebellum. Single AN fibers were isolated with glass micropipettes filled with 3 M NaCl and inserted into the nerve trunk under visual guidance. Sound stimuli were delivered with a dynamic speaker (Supertweeter, RadioShack, Fort Worth, TX) coupled to an earbar that was tightly inserted into the cut ear canal. The stimuli were generated digitally (Tucker-Davis Technologies, Alachua, FL) and were compensated for the acoustic transfer function measured with a probe tube near the eardrum and a 12.7-mm condenser microphone (Brüel & Kjær, Nærum, Denmark). The neural signal was amplified, filtered, timed (1-µs resolution), and displayed using standard techniques.

**Stimuli**

A variety of stimuli (tones, broadband noise, frequency sweeps, current pulses) were used to search for fibers. All fibers encountered were studied. To the extent possible we used identical or equivalent stimuli and analyses as in the first study in this series (Joris et al. 2005). CF was determined with a threshold tracking algorithm. We then sequentially presented long-duration (typically 1 or 5 s, repeated every 1.5 or 6 s, 10 to 30 repetitions) tones at increasing frequency, bracketing CF; the step size was between 25 and 200 Hz. The range of frequencies was chosen to reach the limits of the response area (i.e., extended to frequencies at which there was no response), measured as an increase in firing rate or by the presence of phase-locking. The sound level was usually 50 or 70 dB SPL. Additional levels were tested if time allowed.

Pseudorandom noise bursts (lower cutoff 100 Hz; upper cutoff between 4 and 32 kHz, chosen to be at least an octave above CF) were presented: the same frozen noise token was presented for many repetitions (duration/repetition interval × number of presentations: 1/1.5 s × 40 to 100). The same noise burst was then presented again with the same parameters but inverted in polarity. The stimuli were presented at an overall level of 50 or 70 dB SPL, but if time allowed data collection was repeated at several settings. In the final experiment we tried to obtain responses at multiple SPLs, particularly in fibers with low spontaneous rate (see Fig. 4). In a subset of neurons, rate-level functions to noise were collected to estimate rate threshold. We express the noise sound level as “effective SPL,” which is the small binwidth or “coincidence window” is likely nonphysiological in a binaural context (see Discussion), but is a compromise to bring out maximal temporal detail in the spike trains. Smaller windows result in noisier correlograms, larger windows in smoother but coarser correlograms. The conclusions from the present results are robust against changes in analysis parameters (e.g., coincidence window, number of stimulus repetitions, analysis window, etc.). The rationale and further details of our procedures are provided in Joris (2003) and Louage et al. (2004). With the term “delay functions” we refer both to the correlograms of AN fibers (based on monaural responses) and to the binaural responses of IC neurons to ITDs, either to tones or to noise.

**RESULTS**

**Composite curves and responses to noise in the AN**

Both in the experimental protocol and the subsequent analysis, our procedure for the AN stayed close to the one we used for the IC (Joris et al. 2005). As argued earlier (Joris 2003; Louage et al. 2006), autocorrelation analysis of monaural data affords a straightforward comparison with binaural data. This is so because 1) ITD sensitivity is thought to arise through a process of coincidence detection in the medial superior olive (MSO), which projects to the IC, and 2) autocorrelation analysis is equivalent to a process of coincidence detection at different delays. Indeed, the autocorrelation function (SAC) can be viewed as the simulated output of a hypothetical binaural coincidence detector that is stimulated by noise of varying ITD and that receives two inputs, which are identical in all their properties.

Using data from one neuron, Fig. 1 illustrates the construction of tonal composite curves for AN fibers. The responses needed for this analysis are simply spike times to pure tone stimuli. Figure 1A shows average response rates, which reach the spontaneous rate (horizontal dashed line) at the frequency extremes. This curve effectively corresponds to an isolevel contour of a response area. The first step in the analysis involves the calculation of SACs at each stimulus frequency. Superimposed SACs, shown in Fig. 1D, are equivalent to tonal ITD functions calculated from IC responses to binaural beats. To simplify the figure, three cycles are shown at each frequency. A trivial difference with the IC data is that SACs peak at zero delay: this is entirely as expected for autocorrelation functions. The shape of these SACs is quasi-sinusoidal at all frequencies at which there is phase-locking. This is further illustrated for two frequencies (400 and 600 Hz) with period histograms (Fig. 1, B and C). In contrast to the traditional period histograms, obtained by cutting and stacking postsynaptic time histograms at the stimulus period, the period histograms shown here are obtained by cutting and stacking SACs. These period histograms are not essential for further analysis but are shown for comparison with responses of IC neurons with binaural beats illustrated in the preceding paper (Joris et al. 2005; Fig. 1). Note that the change in coincidence rate is rather similar, in modulation and maximum rate, at 400 and 600 Hz, despite the half-octave difference in stimulus frequency. This can also be seen in the secondary maxima in Fig. 1D, which are similar in amplitude for a wide range of frequencies around CF. Figure 1E (thick curve) shows the composite curve, obtained by pointwise addition of all SACs and subsequent normalization to the sum of the squared firing rate by dividing by the square of the average firing rate (for SACs) or the product of the firing rates to the two stimuli (for XACs). The small binwidth or “coincidence window” is likely nonphysiological in a binaural context (see Discussion), but is a compromise to bring out maximal temporal detail in the spike trains. Smaller windows result in noisier correlograms, larger windows in smoother but coarser correlograms. The conclusions from the present results are robust against changes in analysis parameters (e.g., coincidence window, number of stimulus repetitions, analysis window, etc.). The rationale and further details of our procedures are provided in Joris (2003) and Louage et al. (2004). With the term “delay functions” we refer both to the correlograms of AN fibers (based on monaural responses) and to the binaural responses of IC neurons to ITDs, either to tones or to noise.

**Analysis**

AN fibers were grouped according to spontaneous rate (SR) in two classes: low-SR (SR < 18 spikes/s) and high-SR (SR > 18 spikes/s). The basic analysis of AN responses allowing comparison with the IC involves the construction of autocorrelograms, as described in previous papers (Joris 2003; Joris et al. 2006a; Louage et al. 2004). For proper comparison with our previous study in the IC, we report fibers only with CF < 3 kHz. In this section we give only a general account of the construction of the correlograms. Details on further analysis are described in Results.

Two basic types of correlograms were calculated. Shuffled autocorrelograms (SACs) are calculated from responses to many repetitions of a single stimulus, i.e., either tones, broadband noise (e.g., token A), or the noise inverted in polarity (referred to as token A). SACs are obtained by tallying all intervals between spikes in non-identical spike trains to one stimulus. Cross-stimulus autocorrelograms (XACs) are calculated from responses of the same neuron to two different stimuli, e.g., to noise token A and token A. The autocorrelograms were constructed with 50-µs binwidths and the number of coincidences was divided by the number of stimulus repetitions and stimulus duration. In some cases, referred to as “normalized” correlograms, we also remove the effect of firing rate by...
rates of all the constituent tonal responses. The composite curve shown here is representative for high-SR AN fibers and shows a single dominant peak at 0 delay, flanked by a trough curve shown here is representative for high-SR AN fibers and rates at each frequency. As expected, the composite curve to anticorrelated stimuli (Fig. 1E, thin line) is out of phase with the composite curve to correlated stimuli (heavy line) and both asymptote toward 1 at large delays.

**Damping in the AN**

In the preceding paper we introduced a measure of damping based on a comparison of binaural responses with correlated and anticorrelated noise. The availability of the response to anticorrelated stimuli allows a better delineation of the damping in the autocorrelation functions, especially in cases where the damping appears strong. Figure 1, E and F is such that a value of 1 indicates the absence of temporal correlation between spike trains: this value is obtained for asymptotic values at large delays (the thin lines in these panels are subsequently explained). Comparison of Fig. 1, E and F shows that the response to noise is strikingly more oscillatory than the composite curve to tones.

**Fig. 1.** Illustration of the construction of composite curves for one auditory-nerve (AN) fiber. A: average firing rate to 1-s tones at 50 dB SPL. B and C: period histogram at 400 Hz (B) and near characteristic frequency (CF) (C: 600 Hz) (see arrows in A), calculated from shuffled autocorrelograms (SACs). D: superimposed SACs. To reduce cluttering, the curves are clipped at 3 cycles and smoothed with a 3-point triangular window. Thick curve is SAC for frequency nearest CF (600 Hz). E: composite curve generated by extending the SACs of D over the entire abscissa, followed by pointwise addition of the SACs (unsmoothed) at all frequencies. Thick line in F: SAC to noise. Thin curves in E and F: composite curve and cross-stimulus autocorrelogram (XAC) to anticorrelated stimuli. The abscissa of F also applies to D and E. The fiber had a CF of 593 Hz and spontaneous rate (SR) of 92 spikes/s (dashed horizontal line in A).
irrespective of the exact procedure used to measure the half-width, the envelope is ill-defined in cases as in Fig. 2, A and B (row 1), and this cannot be remedied by changes in the analysis. Comparison of the difcors to noise (Fig. 2B) and to tones (Fig. 2D) shows that they differ from each other, more strongly so than in the IC (Fig. 3 in Joris et al. 2005). For the bottom three neurons illustrated, the difcors to noise are markedly less damped than those to tones, whereas for the top neuron they are similar.

Relationship of damping to CF

In the IC, difcor half-widths decrease as a function of CF (Fig. 6 in Joris et al. 2005). This is expected based on the increase in spectral bandwidth in the auditory periphery (Bourk 1976; Evans 1972; Kiang et al. 1965). With the correlogram analysis illustrated in Figs. 1 and 2, we can compare the dependence of half-width on CF in IC and AN. Responses were obtained from several hundred AN fibers in four animals. In subsequent population figures, all data available for the metrics of interest are shown. Figure 3 provides an overview of the data, plotted as a function of CF. The half-widths of the AN also decrease with CF, both to noise (Fig. 3A) and to tones (Fig. 3B).

Compared with the IC, the AN half-widths to noise are rather tightly distributed at each CF (Fig. 3A). However, at very low CFs, ≤500 Hz, there is a cluster of points with small half-widths that does not seem to follow the general trend. This nonmonotonic trend is also seen in Fig. 2, where the noise half-widths (Fig. 2, A and B) increase from high CF (bottom) to low CF (top; note change in scale of abcissa), but the half-width of the neuron with CF of 208 Hz (row 1) is smaller than that for the 494-Hz neuron (row 2).

In contrast with the half-widths to noise, the half-widths to tones (Fig. 3B) differ markedly for high- and low-SR fibers and do not show the nonmonotonic relationship with CF just described for noise. Most strikingly, the half-widths of the majority of high-SR fibers occupy a small range that changes little with CF except at the very lowest CFs. In low-SR fibers, tonal half-widths occupy a wider range and are generally higher than for high-SR fibers.

The relative magnitude of the half-width to tones and noise is easier to see in Fig. 3C, which shows their ratio. Data points below the dashed horizontal line at a ratio of 1 have larger half-widths to noise than to tones and constitute the vast majority of fibers. Thus overall the response to noise is less damped than that to tones. The exceptions are low-CF/low-SR fibers, which have high thresholds. The AN distribution in Fig. 3C markedly differs from that in the IC (Joris et al. 2005; Fig. 6C), where the data points straddle the line of equality with a tendency for low ratios at low CFs and high ratios at high CFs (i.e., a trend opposite to Fig. 3C).

Dependence on SPL

It is well known that cochlear bandwidth increases with SPL (Carney and Yin 1988; De Boer and de Jongh 1978; Evans 1977; Rhode 1971), so that more damping is expected with increasing level. This is a concern for the comparison between composite curves and noise because the choice of SPL may introduce a systematic bias if not matched for the two sets of responses. On the other hand, it is unclear what “matching” would precisely mean (equal in terms of stimulus power? suprathreshold level? response rate?). We therefore recorded responses at as many different SPLs as the recording time allowed.

Figure 4A shows SAC half-widths to noise at multiple levels. The data are plotted as a function of suprathreshold level, for 39 fibers for which a rate level function to noise was available. There is some decrease in half-width with SPL, but
the effect is remarkably small, both in high- and low-SR fibers. This is also true for a much larger sample of 197 neurons when half-width is plotted versus effective SPL rather than suprathreshold SPL (not shown).

Figure 4B shows half-widths to tones at multiple suprathreshold levels. Half-widths for high-SR fibers are small and, with a few exceptions, show little dependence on SPL. In contrast, half-widths of low-SR fibers increase strongly as the stimulus level approaches rate threshold. The sample of 109 fibers shown here overrepresents low-SR fibers (half of the data sets) because we were particularly interested in their behavior.

Responses of a low-SR fiber, for which data were available over a large range of SPLs to both noise and tones, are shown in Fig. 5 (identified with filled triangles and dashed lines in Fig. 4, A and B). The bottom difcors are near rate threshold for noise (Fig. 5F) and tones (Fig. 5M). The difcors to noise (left column) show only small changes with increasing level: the functions become smoother and the central peak larger, but the overall shape and damping are stable. Nevertheless, the half-widths fluctuate with level (Figs. 4A and 5) but in an uncharacteristic nonmonotonous fashion. This reflects the presence of a shallow “plateau,” which is sometimes seen in difcors near the half-height and which is more prominent in this fiber than in the others studied. In contrast, the difcors to tones show a very orderly change in their shape with increasing level. At low levels, where the isolevel contours (Fig. 5H) show responses to a small range of frequencies, the difcors are very oscillatory compared with the difcors to noise. At high levels the difcors are highly damped, even compared with the difcors to noise.

Comparison of damping in AN and IC

Comparison of damping in Fig. 3 with the equivalent graphs in the preceding paper (Joris et al. 2005; Fig. 6) shows basic similarities but also strong differences. A straightforward way to compare damping at different anatomical levels, and independent of CF, is to express the half-width in terms of the dominant period 1/DF. In weakly damped responses (e.g., Fig. 2B, bottom), several “peaks” or cycles occupy the envelope of the autocorrelogram or noise-delay function, resulting in a high value of HW·DF. On the other hand, in strongly damped responses (e.g., Fig. 2B, top) only a single main peak may occur within the envelope, resulting in a low value of HW·DF. For example, in Fig. 5M, the half-width contains almost exactly three cycles of the dominant period, resulting in an HW·DF value near 3. In contrast, in Fig. 5I the half-width is very similar to the dominant period, resulting in an HW·DF value near 1. In Fig. 6 we replot the half-widths from Fig. 3 and the figure of the preceding paper (Joris et al. 2005; Fig. 6) relative to the dominant period (i.e., multiplied by DF). For AN fibers (left column), the half-width and DF values are taken from difcors of correlograms to noise and tones (left column: HW\(_N\) and DF\(_N\) for noise, HW\(_T\) and DF\(_T\) for tones). For IC neurons (right column), the half-width and DF values are taken from difcors of noise-delay functions (HW\(_{ND}\) and DF\(_{ND}\)) and composite curves (HW\(_{CC}\) and DF\(_{CC}\)).

The IC noise data (Fig. 6C) are rather uniformly spread over a fourfold range and show little dependence on CF. The range is more compressed in response to tones (Fig. 6D), with most values between 1 and 2. The AN data are most strikingly

![Fig. 3. Comparison of damping to noise and tones, as a function of CF.](https://www.jn.org uploads/Fig_0003.jpg)

A: half-widths of difcors obtained from autorecorlograms to noise (193 fibers). All responses were obtained at 70 dB overall SPL. The average effective SPL and suprathreshold level were, respectively, 47 and 28 dB. B: half-widths of composite curves to tones (101 fibers). SPL was between 50 and 70 dB and averaged 55 dB. Average suprathreshold level was 28 dB. C: ratio of tonal to noise half-width (86 fibers). Dashed line indicates equality. Low-SR fibers: triangles; high-SR fibers: +.

![Fig. 4. Dependence of half-width to noise (A) and tones (B) on suprathreshold level.](https://www.jn.org uploads/Fig_0004.jpg)

A: 39 fibers, 128 data points. B: 109 fibers, 156 data points. Values in B are clipped at 14 ms; difcors for fiber with solid triangles and dashed line are shown in Fig. 5. Low-SR fibers: triangles; high-SR fibers: +.
The change in shape of the AN correlograms may reflect the changes in amplitude and phase spectrum toward the cochlear apex (Cooper and Rhode 1996; van der Heijden and Joris 2003, 2006), although somehow this is not reflected in the ND functions of the IC.

The discrepancy between damping of low-CF AN and IC neurons to noise is interesting because it points to noncochlear factors influencing the shape of delay functions at the level of the IC. So far, we have discussed only the degree of damping in delay functions, without paying attention to the height of the functions. To better understand the differences between the noise responses in AN and IC, we now examine the relationship between peak height and damping.

Rectification in AN and IC

AN and IC neurons show different degrees of “rectification” in their autocorrelograms and ND functions, i.e., different degrees of asymmetry in antiphase response parts. In some neurons (see, e.g., inset of Fig. 8B, bottom left) the delay function to anticorrelated noise is a rather faithful mirror image of the function to correlated noise. In such cases, the delay functions have peaks and troughs that straddle the response to uncorrelated noise or, equivalently, the responses at large ITDs. In other neurons (e.g., insets of Fig. 7, left) the response to uncorrelated noise (and to large ITDs) is low: here the delay functions consist of large peaks and shallow troughs. The relevance here of the degree and form of rectification is that these may influence the shape of the delay functions (as explained further in this section). As a simple measure of rectification, we compared the maximal response to correlated noise with the response to uncorrelated noise.

For AN fibers, the ratio of the maximal response (maximal coincidences) to correlated noise relative to the response to uncorrelated noise is simply obtained from the normalized shuffled autocorrelogram (SAC). Indeed, due to the normalization procedure, the response to uncorrelated noise averages out to 1, and the ratio of the maximal response to correlated noise versus the average response to uncorrelated noise is thus given by the peak value of the normalized correlogram: the correlation index (CI) (Joris et al. 2006a). The CI is shown for our population of AN fibers in Fig. 7A.

For binaural IC neurons, the numerator of the comparable ratio is the firing rate to correlated noise at the “best delay,” here defined simply as the ITD giving the maximal firing rate. The denominator (response to uncorrelated noise) was obtained in either of two ways, illustrated with the noise-delay functions in Fig. 7 (left column). In 53 neurons, responses to uncorrelated noise were available over a range of ITDs. This response was always flat as a function of ITD and we therefore averaged the firing rate over all ITDs. The resulting CI values are shown as solid circles in Fig. 7B. When the response to uncorrelated noise was not available, it was estimated by measuring the average rate at large ITDs, where the responses to correlated and anticorrelated noise converged. We averaged the firing rates of points where ND functions to correlated and anticorrelated noise crossed, but only at ITDs that were outside the range of ITDs corresponding to the half-width (see example in Fig. 7, top left column). The resulting CI values are shown as crosses in Fig. 7B. The distribution for CI values obtained with actual responses to uncorrelated noise (Fig. 7B, solid circles) is different from the IC data for the noise responses (Fig. 6A). Most noise dircors have more than two cycles per half-width, and the distribution is narrow and strongly CF dependent, unlike the IC (Fig. 6C). The values for tones (Fig. 6B) show a clear segregation between high- and low-SR fibers and straddle the IC distribution (Fig. 6D).

Clearly, it is easy to account for the damping to tones in the IC (Fig. 6D) based on the distribution in the AN (Fig. 6B), but the different distribution for noise between AN and IC merits further investigation. The trend in Fig. 6A was already evident in Fig. 2, A and B: the noise responses show two or more cycles of fine structure within the envelope half-width, except at the lowest CF (top row) where a single central peak stands out.
similar to the larger set of data points obtained with estimated values to uncorrelated noise (Fig. 7B, ×), with means that are not statistically different (t-test, \( P > 0.05 \)).

As shown earlier, SACs of AN fibers reach higher CI values in low-SR than in high-SR fibers and the CI decreases with increasing CF (Louage et al. 2004; Fig. 4; note that CI is the same as peak height of the normalized SAC). This is also the case for the fibers of the present sample (Fig. 7A). The distribution in the IC (Fig. 7B) is quite different. At CFs roughly >1 kHz the binaural data tend to show a wide range of CI values, with some values that are higher than those in the AN. At lower CFs the opposite is the case: values in the IC are generally lower than those in the AN. In combination, Figs. 6, A and C and 7 show that AN fibers with very low CF tend to show highly peaked and strongly damped delay functions, whereas in the IC there is more variety and less CF dependence both in “peakiness” and in damping.

The CI metric gives a very simple indication of the degree to which stimulus correlation affects number of coincidences (in the AN) or response rate (in the IC). Binaural neurons show a variety of relationships between firing rate and interaural correlation, ranging from expansive, linear, to compressive (Albeck and Konishi 1995; Shackleton et al. 2005; Yin et al. 1986). An expansive relationship boosts response rates at favorable ITDs, which should result in an apparent stronger damping of the delay function. On the other hand, a compressive dependence of firing rate on interaural correlation should result in less damping. We therefore expect an inverse correlation between CI and half-width: neurons with expansive rate-correlation functions and high CI should have a smaller half-width, whereas low CI values should be associated with high half-widths. In Fig. 8, half-width is expressed normalized to DF as in Fig. 6 and CI is measured as in Fig. 7. There is indeed an inverse correlation for both the AN (Fig. 8A) and IC (Fig. 8B), which is weak (\( A: r = -0.54, B: r = -0.3 \)) but significant (\( P < 0.001 \) in both cases). That the correlation is weaker in the IC than that in the AN should not surprise because of the diversity in ND functions. The inverse relationships in both panels indicate that indeed neurons with strongly rectified delay functions (high CI) tend to be strongly damped, whereas neurons with oscillatory (weakly damped) delay functions tend to show little rectification (low CI). The correlograms and ND functions shown in Fig. 8 (insets) illustrate some of the more extreme values in the distributions.

**Relationship between CF and DF**

In the IC, we found that ITD sensitivity to noise was dominated by frequencies near CF, whereas the ITD sensitivity...
to tones tended to be dominated by frequencies below CF (Joris et al. 2005). Figure 9 shows the same analysis for AN fibers. In the left panels, the dFCor DF is compared with CF. In response to noise (Fig. 9A), DF and CF are well correlated, as reported earlier (Fig. 13 in Louage et al. 2004). Deviations occur only at CFs above a few kilohertz, where DF is lower than CF likely due to the limits on phase-locking to fine structure. This explanation is not sufficient to account for the trend with tones (Fig. 9B), where the DF is systematically biased toward lower frequencies than CF, over nearly the entire range of CFs, much as we reported for ITD sensitivity in the IC (Fig. 9C). When compared directly (Fig. 9D), the DF to tones is generally smaller than the DF to noise. In summary, the temporal response to tones shows a frequency weighting dominated by frequencies below CF.

Examination of DFs to noise with increasing SPL shows a systematic converging pattern (Fig. 9C). DFs increase in fibers with DF > 1 kHz, and decrease in fibers with DF > 1 kHz. This trend was reported earlier for a smaller sample (Louage et al. 2004) and is consistent with findings using a different analysis (Evans 1977).

**Discussion**

Yin et al. (1986) were the first to report surprisingly linear responses to broad- and narrowband stimuli in the cat IC. They studied ITD sensitivity of low-CF neurons to tones and noise and found a reasonably good match for several response features, but it was unknown whether this quasi-linear behavior was a central or a peripheral feature. We compare damping as a function of monaural delay in the AN and, in the preceding paper, as a function of ITD in the IC, in each case using responses to tonal stimuli and to broadband noise.

The first main finding concerns the comparison of tones to noise: in the AN, damping for tones differs strongly from that to noise, in contrast to the IC where it is more balanced. This is most strikingly seen by the comparison in Fig. 6 of responses in the AN (left column) and IC (right column). The good fit between composite curves and ND functions in the IC, first reported by Yin et al. is thus even more surprising than was apparent from its original report. Based on peripheral physiology, larger differences between these responses would be expected than in fact are found.

The second main finding concerns a subset of the data: at the lowest CFs, the delay functions are more oscillatory in IC neurons than in AN fibers (Fig. 6, A and C) and the effect of stimulus correlation on response magnitude is smaller in the IC than in the AN (Fig. 7). This is a counterintuitive result because a reduced dependence is detrimental to the role of these neurons in the detection of temporal differences between the ears.

The AN data show a rather complex picture of differences between high- and low-SR fibers and various effects of SPL and CF. We first discuss the findings to noise, then to tones, in each case including a comparison to the IC.

**Broadband noise: damping in AN and IC**

Damping in the IC shows little dependence on SPL and an orderly increase (decrease in half-width) with CF (Joris et al.
The same main trends are found in the AN. Generally, AN half-widths decrease in an orderly fashion with CF (Fig. 3A), are narrowly distributed with CF (Fig. 6A), and are similar for high- and low-SR fibers (Figs. 3A and 6A). Because the latter two populations differ on many other counts (Figs. 3, 4, 6B, 7A, and 8A), the similarity of their half-widths to noise suggests that these half-widths are dominated by cochlear (presynaptic) events.

The most striking difference that we find between IC and AN is how the half-width to noise depends on CF. When expressed relative to the dominant period, damping to noise is strongly dependent on CF in the AN (Fig. 6A), but not in the IC (Fig. 6C). Moreover, whereas the AN half-widths at the lowest CFs tend to be smaller than in the IC, the opposite is the case at higher CFs. This puzzling difference between AN and IC necessitates a separate discussion for different frequency ranges.

At CFs roughly >500 Hz, most AN half-widths contain more than two cycles of the dominant period. This is large compared with the IC (Fig. 6, A and C), for which we see two possible mechanisms. If the dependence of neuronal output rate on stimulus correlation is more expansive in the IC than in the AN, peak values of the noise-delay function in the IC would be boosted, resulting in lower half-widths in the IC than in the AN. The process of coincidence detection in the MSO would be expected to generate such an expansive relationship. This interpretation receives some support from Fig. 7, which shows that IC neurons >500 Hz indeed often have higher CI values than AN fibers, and from Fig. 8, which shows a lack of neurons with high CI values combined with large half-widths. However, there clearly are also many IC neurons with both small half-width and small CI value (Fig. 8B), so that other mechanisms must be at play. A second factor that would affect the shape of ND functions is convergence at the level of the IC, more specifically the alignment of the ND functions of the inputs. Such convergence has been invoked for the stronger damping in the midbrain of the barn owl (Mazer 1998; Peña and Konishi 2000; Takahashi and Konishi 1986) and for other features of ITD sensitivity at the level of the IC (McAlpine et al. 1998; Shackleton et al. 2000).

For progressively more apical AN fibers, there is an abrupt downturn in half-width, from values near two cycles of the dominant period to <0.5 cycle (Fig. 6A). Examination of the autocorrelation functions (Fig. 2, A and B) shows that there is a qualitative change toward very low CFs, so that the autocorrelations are no longer properly described as oscillatory. What is interesting in the context of this study is not the downturn in itself, but the observation that it is not found in the IC: even for the neurons with the lowest CFs studied, ITD sensitivity is more oscillatory than expected from the temporal properties of AN neurons of similar CF. This is even more striking when it is taken into account that in correlograms of bushy cells, which provide monaural inputs to MSO neurons, the central peaks are even higher relative to the side peaks than in the AN (Lounge et al. 2005). Mismatches provide a possible explanation in the spectral tuning properties of inputs. ND functions in the IC may not show the highly peaked shape of the correlograms of AN fibers or bushy cells because of incoherence or decorrelation between inputs to MSO neurons. We have shown earlier that the sharp central peaks of the correlograms of AN fibers and bushy cells are reduced in amplitude by partial decorrelation of stimulus waveforms (Lounge et al. 2006). Decorrelation could also arise internally, consequent to differences in the properties of the inputs that converge on an MSO neuron. For example, mismatches in threshold, CF, bandwidth, phase spectrum, and so forth would cause incoherence or a decorrelation between the spike trains that feed into a coincidence detector.

The mismatches could be monaural (between bushy cells converging from the same side on an MSO neuron) or binaural (between bushy cells converging from ipsi- and contralateral). To the extent that collicular inputs carry temporal information, such mismatches may even originate at the level of the IC. We have presented preliminary evidence (Joris and van der Heijden 2007) from IC recordings that both monaural and binaural spectral mismatches occur. Also, low-CF IC neurons show a wider range of spectral bandwidths than AN fibers (McLaughlin et al. 2007). Finally, coincidence counts on spectrally mismatched AN fibers are consistent with some features of IC responses (Joris et al. 2006b). These observations suggest that spectral mismatches explain key features of binaural ITD sensitivity at the level of the midbrain. The effects of such mismatches are expected to be larger at low CFs than at mid-CFs because the phase transfer functions change more quickly at the cochlear apex than at more basal locations (Joris et al. 2006b; van der Heijden and Joris 2006).

Tones: damping in AN and IC

In response to tones, there are clear differences between high- and low-SR fibers. Low-SR fibers have a “hard” rate threshold so that pure tones at low SPLs evoke a response over a limited frequency range, which results in very oscillatory composite curves (Fig. 5M). With increasing SPL, the range of effective frequencies increases and the composite curve increases in damping (Figs. 4B and 5, I–M). In contrast, their response to noise, even at very low SPLs, contains all components falling in the passband of the cochlear filter, and the damping in correlograms to noise is rather invariant with SPL (Figs. 4A and 5, B–F).

In high-SR fibers, the composite curve to tones shows an extreme degree of damping (Figs. 1E, 2, C and D, 3B, 4B, and 6B), which is nearly always greater than the same fibers’ damping to noise, independent of SPL (Figs. 3C and 4). Thus if one compares IC neurons to high-SR fibers, which are the most numerous fibers in the AN, the differences are striking and point to a much greater discrepancy between tonal and broadband responses in the AN than in the IC. High-SR fibers have not only higher SR but also a lower absolute threshold and smaller dynamic range than low-SR fibers (Liberman 1978; Schalk and Sachs 1980; Winter et al. 1990). The presence of spontaneous spikes softens the threshold nonlinearity; even at very low SPLs, single tones induce phase-locking over a wide range of frequencies. Moreover, the resulting autocorrelograms are similar in amplitude over a wide range of frequencies due to the limited dynamic ranges of firing and phase-locking (Johnson 1980). This can be seen in the peak amplitudes of the SACs in Fig. 1D, which show little change over the range of 400 to 900 Hz. As a result, the summed responses (Figs. 1E and 2, C and D) suggest a wider filter with a more damped response than the response to noise.
Use of autocorrelograms

An essential function of the MSO is to transform temporal structure in afferent signals into a rate code. In the present and preceding papers, we compare average firing rate of binaural neurons with the temporal structure of responses of monaural neurons. The tool to make such comparison is the autocorrelogram, which can be viewed as the output of the simplest possible coincidence detector receiving two identical inputs, for a range of delays. The attraction of the correlogram analysis is that it allows an assessment of temporal properties in a way that is more physiological (in a binaural context, i.e., a coincidence analysis) than for example vector strength or Fourier analysis (Goldberg and Brown 1969) or reverse correlation (De Boer and Kuyper 1968). One may argue, however, that the comparison of correlograms with ND functions is inappropriate. The “coincidence window” of MSO neurons is not known, but is likely larger than the 50-μs window used in our coincidence analysis. The number of inputs to an MSO neuron is also unknown, but it surely is larger than one neuron from each side. Moreover, the excitatory monaural inputs to the MSO—the bushy cells of the cochlear nucleus—themselves receive convergent AN input. In fact, the autocorrelograms of bushy cells differ significantly from their AN inputs (Louage et al. 2005), although we have not examined their damping. Finally, MSO neurons also receive inhibitory inputs and our comparison is not with MSO but with IC, again involving at least one additional synapse and many additional possible sources of input besides the MSO. If a given AN fiber is only a distant and partial input to an IC neuron, does it make sense to compare autocorrelograms of the former with firing rates of the latter?

Our goal is not to model binaural responses, which would clearly require a different approach (e.g., Brughera et al. 1996; Shackleton et al. 2000; Zhou et al. 2005). Rather, our analysis is in the tradition of trying to understand properties observed at one level from the minimal number of elements at a lower level. SACs represent a uniquely defined boundary case: they provide a means to study the temporal distribution of spikes in a quantitative format readily comparable to real binaural responses. Increase of the number of inputs to a coincidence detector > 2, or of the integration window beyond the refractory period, necessitates parametric choices that go beyond the simple counting of coincidences. Despite their unrealistic simplicity, coincidence counts at different delays capture much, though not all, of the rate behavior observed at the level of the IC. Discrepancies between the two levels guide us to identify physiological and anatomical circuit features that are critical to obtain the ITD sensitivity observed at the level of the midbrain.

Origin of linearity in the IC

In their seminal IC paper, Yin et al. (1986) found overall stronger damping in tonal composite curves than in ND functions and remarked that this difference “could be due to suppression of those frequencies near the edges of the response area, as in sideband inhibition.” Neural sideband inhibition is probably not relevant because the difference is actually larger in the AN than in the IC and because inhibition is not present at the level of the AN. However, Yin et al. (1986) proposed cochlear two-tone suppression may be the underlying mechanism. Two-tone suppression is a neural and mechanical phe-


