Binaural detection with spectrally nonoverlapping signals and maskers: evidence for masking by aural distortion products

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

Download date: 16. Nov. 2023

Binaural detection with spectrally nonoverlapping signals and maskers: Evidence for masking by aural distortion products

Marcel van der Heijden and Constantine Trahiotis
Surgical Research Center, Department of Surgery (Otolaryngology) and Center for Neurological Sciences, University of Connecticut Health Center, Farmington, Connecticut 06030

Armin Kohlrausch and Steven van de Par
Institute for Perception Research (IPO), P.O. Box 513, NL-5600 MB Eindhoven, The Netherlands

Thresholds were measured for diotic tonal signals in the presence of interaurally delayed bands of Gaussian noise. When the signal frequency was 525 Hz, the spectrum of the noise was either below (highest frequency, 450 Hz) or above (lowest frequency, 600 Hz) the frequency of the signal. When the signal frequency was 450 Hz, the spectrum of the noise was always above the signal frequency (lowest frequency, 600 Hz). Signals had a 250-ms duration and were temporally centered within the 300-ms long bursts of noise. The spectrum level of the noise was 60 dB. Thresholds obtained in all three conditions varied essentially sinusoidally with the interaural delay of the noise. For signals below the spectrum of the noise, the periodicities within the data were close to, but not identical with, the periodicities of the *signals*. This outcome is discussed in terms of masking produced by aural distortion products stemming from interactions within the bands of noise [cf. van der Heijden and Kohlrausch, J. Acoust. Soc. Am. **98**, 3125–3134 (1995)]. For signals above the spectrum of the noise, the periodicities in the data suggested that masking was produced by components within the band of noise. Patterns within the data are also discussed in terms of limitations concerning the magnitude of external delays that can be matched by internal delays that are incorporated in modern models of binaural processing. © *1997 Acoustical Society of America.* [S0001-4966(97)03211-6]

PACS numbers: 43.66.Pn, 43.66.Dc [JWH]

INTRODUCTION

In a recent study, van der Heijden and Kohlrausch (1995) showed that aural distortion products evoked by interactions among the components of a band of noise determined the detectability of a tonal signal whose frequency was *below* the spectral region of the noise. The level of the noise was low enough to preclude similar effects due to remote masking (e.g., Bilger and Hirsh, 1956). Van der Heijden and Kohlrausch found that the distortion products responsible for their ''downward'' masking effects had level-dependent phases that were similar to those found with odd-order distortion products such as the cubic difference tone (e.g., Goldstein, 1967). In addition, van der Heijden and Kohlrausch found that aural distortion products appeared to play no role when the frequency of the signal was above the spectral region of the noise (an ''upward'' masking condition). Their findings are consistent with well-known physiological and psychophysical observations concerning distortion products.

It occurred to us that a binaural paradigm could provide a further test of the ability of auditory distortion products to produce ''downward'' masking. The challenge was to differentiate between masking effects produced by components of a noise stimulus per se and masking effects produced by internally generated distortion products. Our strategy was to employ interaural delays of a band of noise and to use periodicities within the data to determine whether detectability was due to: (1) components within the band of noise, in this case remote from the frequency of the signal; or (2) distortion products having spectral components in the *same* frequency region as the signal. Said differently, we attempted to use interaural delays of a band of noise to separate off-frequency masking (i.e., masking due to spectral components spectrally distant to the signal frequency) from on-frequency masking (i.e., masking due to distortion products adjacent to and/or overlapping with the signal frequency).

Our expectation was that, if masking were ''on-frequency'' due to distortion products, then the pattern of thresholds, as a function of interaural delay of the noise, would reflect the frequency of the signal. That type of outcome was reported in the classic studies of Rabiner *et al.* (1966) and Langford and Jeffress (1964), who measured the detectability of tonal signals masked by Gaussian noise having components in the same spectral region as the signal. For the type of on-frequency masking which they studied, the data showed oscillations at the frequency of the signal as the masking noise was interaurally delayed.

To our knowledge, there are no data available concerning how binaural detectability varies with interaural delay when signal and masker occupy different spectral regions. We are aware of only two studies dealing with binaural processing in ''off-frequency'' conditions. McFadden *et al.* (1972) measured masking-level differences in a tone-on-tone paradigm with the signal placed spectrally above or below the sinusoidal masker and Hall *et al.* (1983) measured binaural detection in a notched-noise experiment. Neither of those two studies incorporated stimulus conditions involving interaural delays. Therefore, the data obtained in those studies may not directly bear on issues of interest here. Conse-

quently, what the patterning of thresholds is as a function of delays in the maskers in the off-frequency case is an open question, which the data obtained in this investigation will help answer.

I. METHOD

Detection thresholds were determined using a three-interval forced-choice adaptive procedure (Levitt, 1971). Each trial consisted of three 300-ms observation intervals each separated by 200 ms. The signal occurred randomly, with equal *a priori* probability in each of the three intervals. The listeners were provided with correct-answer feedback via a computer terminal. Each estimation of threshold began with the signal being easily detectable. The level of the signal was decreased after two consecutive correct responses and was increased after each incorrect response. This procedure tracked the 70.7% correct point of the psychometric function. The step size was 8 dB at the beginning of each run, was reduced to 4 dB after the second reversal, and to 2 dB after the fourth reversal. Ten more reversals were obtained using 2-dB steps. An estimate of threshold was obtained by calculating the median of the levels over the ten last reversals. Final thresholds are the average of three such estimates.

Thresholds were obtained for tonal signals in the presence of a band of noise. In different conditions, the frequency of the signal was either below or above the frequencies composing the band of noise. When the band of noise had components ranging from 600 to 1100 Hz, the frequency of the signal was either 450 or 525 Hz. When the band of noise had components ranging from 0 to 450 Hz, the frequency of the signal was 525 Hz. Thresholds were measured with several interaural time delays (ITDs) of the noise ranging from 0 to 2470 μs in steps of 130 μs. The bands of noise had a duration of 300 ms including 20-ms, cosine-squared on/off ramps and had a spectrum level equivalent to 60 dB SPL. The duration of the signals was 250 ms (including 20-ms, cosine^2, on/off ramps) and the signals were temporally centered in the band of noise. The signals were always presented diotically (So) resulting in a binaural configuration commonly referred to as NτSo.

All stimuli were digitally generated utilizing a 32-kHz sampling rate and were played out using 16-bit D/A converters. Before each block of trials that led to an estimate of threshold, a 4-s long circular buffer of Gaussian noise was calculated and independent, 300-ms long, samples of that noise were drawn randomly to produce the noise stimulus in each observation interval. The buffers of noise were constructed by first drawing independent samples from a Gaussian distribution and then applying a discrete Fourier transform to those samples which resulted in a spectrum having a spacing of 0.25 Hz between components. The spectral components outside the desired passband were set to zero and an inverse Fourier transform yielded the desired 4-s-long circular buffer of band-limited Gaussian noise. Noises constructed in this manner have a long-term spectrum with extremely steep spectral edges.

The testing of the conditions was completely randomized, except that the estimates of thresholds obtained with

signal frequencies of 450 and 525 Hz in the presence of the higher-frequency noise were collected in pairs. Three of the authors (AK, SP, and MH) participated in the experiment. All listeners had normal hearing and had extensive experience in formal binaural listening tasks. Initial testing was conducted in single-walled, sound-attenuating chambers housed in laboratories at IPO, The Netherlands, using Beyer DT 880 headphones. Follow-up experiments were conducted at IPO and at the psychoacoustics laboratory at the University of Connecticut Health Center using TDH-39 earphones at both institutions.

II. RESULTS

The behavioral thresholds are plotted in Fig. 1 along with curves representing the cosine functions that best fit the respective sets of data. In Fig. 1, panels (a) and (b), respectively, contain data obtained when the frequency was 525 Hz (closed triangles) or 450 Hz (closed squares) and when the noise had components ranging from 600 to 1100 Hz. Panel (c) of Fig. 1 contains data obtained when the frequency of the signal was 525 Hz and the components of the noise ranged from 0 to 450 Hz (closed circles).

The data points represent means calculated across the three listeners and the error bars represent the standard errors of those means. Because we are principally interested in the patterning of the data as a function of ITD, individual differences in overall threshold were removed during the calculation of the standard errors in each plot. This was done by subtracting the mean of the data of each listener from the grand mean, in each signal condition, respectively.

Let us first consider data obtained with the higher-frequency band of noise [Fig. 1, panels (a) and (b)]. In both cases, the thresholds vary with ITD in a manner that appears to be approximately cosinusoidal. Note that the patterns of thresholds obtained with the two signals are different, especially for ITDs greater than 1000 μs. When the frequency of the signal was 525 Hz [panel (a)], thresholds increased more steeply for delays greater than 1000 μs than did the thresholds obtained when the signal was 450 Hz [panel (b)]. In addition, when the signal frequency was 525 Hz, a maximum in threshold occurred when the ITD was 1690 μs and performance improved as ITDs were increased to 2470 μs. In contrast, when the signal frequency was 450 Hz, thresholds increased for ITDs of up to 2080 μs or so.

We examined periodicities within the data using the simplifying assumption that the thresholds varied as a cosinusoidal function of ITD. We found the best fitting cosine function (based on a least-squares criterion) for the data shown in panels (a) and (b). Amplitude and frequency were allowed to vary, but phase was constrained to be zero. This was done because a value of zero ITD would be expected to lead to the poorest performance (i.e., a maximum in threshold) given that the signals were presented in the So configuration. That is, the zero ITD in the noise results in an NoSo condition, a binaural configuration that does not contain interaural differences.

When the frequency of the signal was 525 Hz [panel (a)], the data were best fit by a cosine function having a frequency of 540 Hz and 84% of the variance in the data was
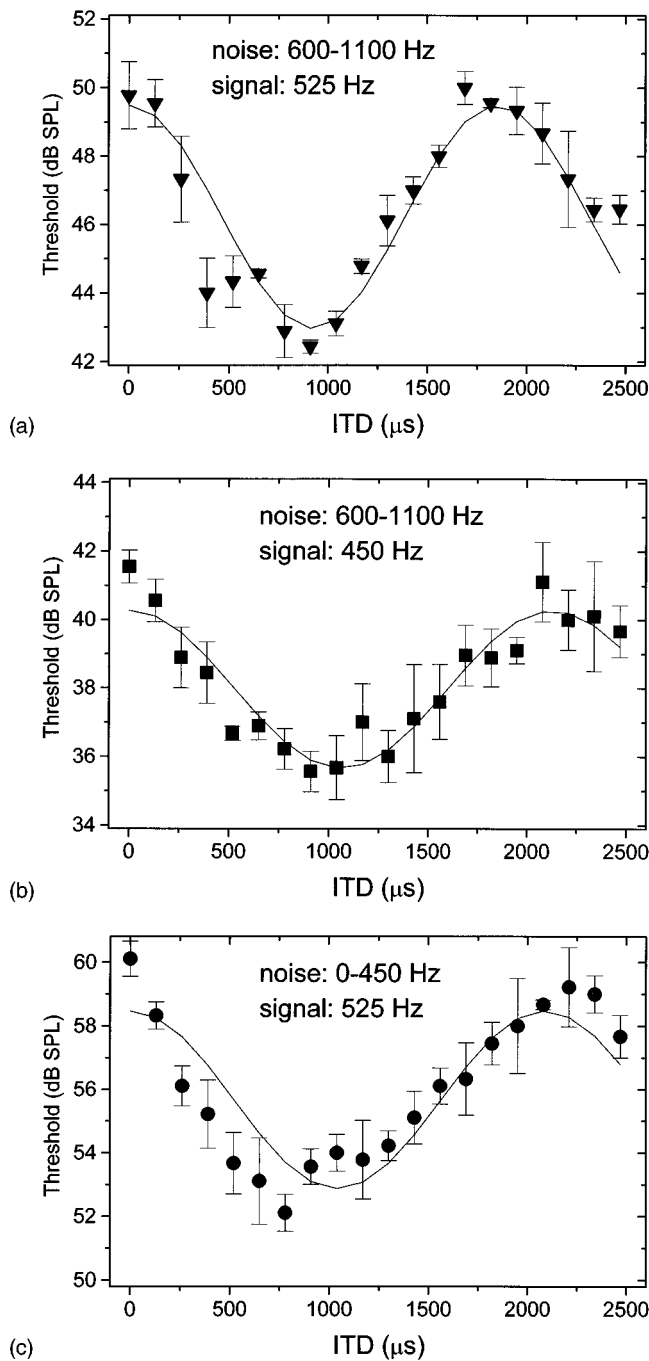
FIG. 1. Average thresholds of the three listeners as a function of ITD of the noise. Error bars indicate across-listener standard errors computed after differences in overall threshold were removed (see text). The data points in panels (a) and (b) were obtained when the spectral content of the noise ranged from 600 to 1100 Hz and when the frequency of the signal was either 525 Hz [panel (a), closed triangles] or 450 Hz [panel (b), closed squares]. The data points in panel (c) (closed circles) were obtained when the spectral content of the noise ranged from 0 to 450 Hz and the frequency of the signal was 525 Hz. Solid lines in each panel indicate cosine functions that best fit the data.

accounted for by that function. That function is represented by the solid line in panel (a). Note that this best fitting frequency of 540 Hz is well *below* the spectral content of the noise and close to the frequency of the signal. This outcome is consistent with the hypothesis that the signal was being masked by aural distortion products, an interpretation that

will be discussed in detail after other data are presented.

When the frequency of the signal was 450 Hz [Fig. 1, panel (b)], the data were best fit by a cosine function having a frequency of 469 Hz (solid line). That frequency accounted for 87% of the variance in the data. Although the spectral content of the noise was the same as when the frequency of the signal was 525 Hz [panel (a)], the frequency that best fits the data is now 71 Hz lower than before. As before, the best fitting frequency is well *below* the spectral content of the noise and close to the frequency of the signal. Overall, based on the frequencies that best fit the data, the patterning of the data in panels (a) and (b) of Fig. 1 is consistent with the hypothesis that the signals were masked by aural distortion products.

Let us now, using the same fitting methods as before, consider how well the data are fit by other frequencies besides the best fitting ones. This will provide an indication of how robust the data are in terms of being characterized by the single cosine functions shown in panels (a) and (b) of Fig. 1. Panel (a) of Fig. 2 shows the percentages of variance accounted for in the data presented in panels (a) and (b) of Fig. 1 as a function of the frequency used to fit the data. Note that the frequencies which account for the largest percentages in the data are clearly different for the two signal frequencies, despite the fact that the external or physical noise was the same in the two conditions. Also note that specification of a *spectral region* rather than a particular frequency appears to be a more accurate description of the quality of fits to the data by single cosine functions. Essentially identical amounts of variance were accounted for by a small band of frequencies surrounding the best fitting one. Still, it is clearly the case that the spectral regions that provide the best fits to the data are those that were expected to provide on-frequency masking due to aural distortion products.

Let us now turn to the data obtained with the lower-frequency band of noise [Fig. 1, panel (c)]. The reader is reminded that the frequency of the signal (525 Hz) in this condition was *above* the spectral content of the noise, which ranged from 0 to 450 Hz.

The behavioral thresholds in panel (c) vary as a function of ITD, indicating that interaurally delaying a noise can differentially affect the detectability of a signal placed spectrally above the highest frequencies in the noise. The maximum release from masking, about 8 dB, occurred when the ITD was 780 μs. The solid line in Fig. 1, panel (c), represents the best fitting cosine function which, in this case, had a frequency of 479 Hz and accounted for 79% of the variance in the data. A frequency of 479 Hz is 29 Hz above the highest components of the noise and 46 Hz below the frequency of the signal.

Panel (b) of Fig. 2 shows the percentages of variance accounted for the data in panel (c) of Fig. 1 as a function of the frequency used to fit the data. Frequencies in the region between about 450 and 510 Hz account for between 72% and 79% of the variance of the data. In this case, the best fitting cosine functions are well *below* the signal frequency and slightly above the highest components of the noise. This outcome, taken in conjunction with the data discussed earlier, suggests that different processes or mechanisms may mediate

2968   J. Acoust. Soc. Am., Vol. 102, No. 5, Pt. 1, November 1997

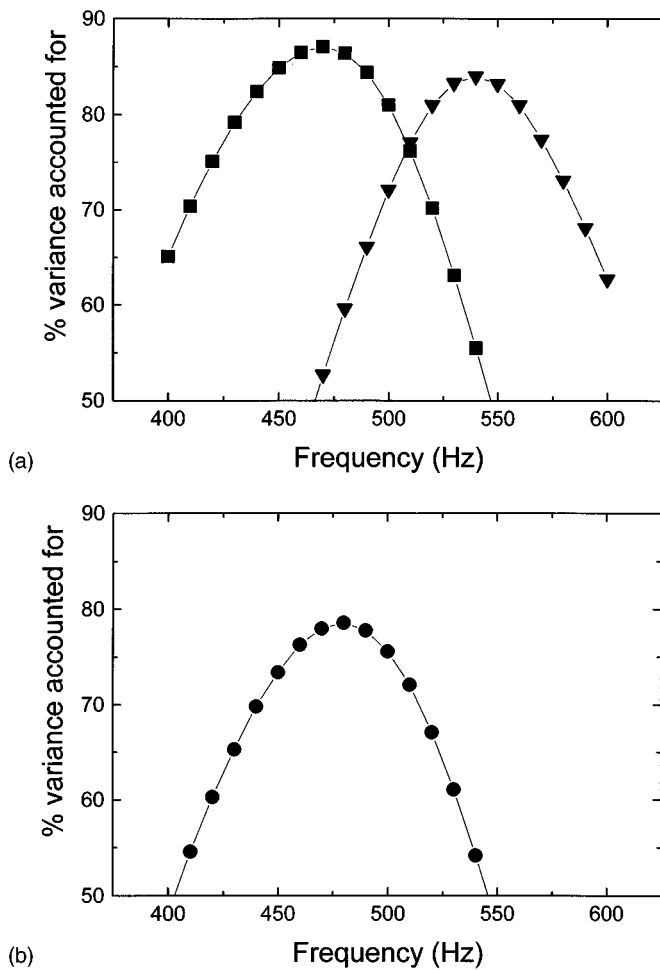van der Heijden *et al.*: Aural distortion and binaural detection   2968

FIG. 2. The percentage of variance in the data of Fig. 1 accounted for by fitted cosines as a function of the frequency of the fitting cosine functions. In panel (a), this value is shown for the thresholds obtained when the spectral content of the noise ranged from 600 to 1100 Hz. The two different curves represent the two different signal frequencies: 450 Hz (closed squares) and 525 Hz (closed triangles). In panel (b), the percentage of variance accounted for is shown for the thresholds obtained when the spectral content of the noise ranged from 0 to 450 Hz and the signal frequency was 525 Hz (closed circles).

binaural detection depending on whether the frequency of the signal is below or above the spectral content of the external noise.

Although the data presented in the three panels of Fig. 1 are well fit by cosine functions, close visual inspection indicates that there are systematic departures from the best fitting cosine functions, especially for the thresholds obtained with the smaller values of ITD. Among the most striking examples are the thresholds in Fig. 1, panel (c), for TDs ranging from 260 to 780 μs. Those data clearly suggest a much more rapid decline in threshold than that described by the best fitting function. We were also concerned that those data appear to have a second maximum at an ITD of about 2210 μs that is located beyond the maximum displayed by the best fitting cosine function of 479 Hz. These aspects of the data are addressed next in Sec. III.

III. DISCUSSION

We begin by discussing the results in terms of Durlach's equalization-cancellation model (Durlach, 1963, 1972). In an

NπSo condition such as those investigated here, equalization is accomplished via internal delays that compensate for the ITD in the noise. The stimulus condition is thereby transformed into a new configuration in which the noise is, ideally, interaurally identical (No). After equalization, the signal contains a time-delay equal to the internal delay required to equalize the noise. In this manner, the NπSo condition becomes, after equalization, effectively equivalent to NoSτ, where τ is the time delay of the signal corresponding to the internal delay required to match the external delay of the noise.

Now, in our experiment, if the listeners were able to match (internally) the ITD of the noise, then one would expect that NπSo thresholds would vary in the same manner as would thresholds obtained in an NoSτ condition with the same signal frequency. In order to see if this were true, we retested the same listeners in the three main conditions of our original experiment utilizing an NoSτ stimulus configuration. For each signal frequency, we used several ITDs that were equivalent to phase shifts of up to 180 deg. In addition, for reasons discussed later, we also obtained data using an NπSo stimulus condition.

The new data, obtained in the NoSτ condition, are plotted in the three panels of Fig. 3 as open symbols. The data represented by closed symbols are replotted from Fig. 1.

When the signal was spectrally below the noise [panels (a) and (b) of Fig. 3], thresholds obtained with ITDs of the signal greatly overlap thresholds obtained with ITDs of the noise, provided that the ITD was less than 500 μs or so. For larger values of ITD, thresholds obtained with ITDs of the signal are consistently *lower* than thresholds obtained with ITDs of the noise. Panel (c) of Fig. 3 contains similar trends, save for the fact that the thresholds obtained with ITDs of the signal and thresholds obtained with ITDs of the noise now overlap for ITDs of up to about 800 μs.

We believe that the overlapping of the thresholds in the NπSo and NoSτ conditions is evidence that the external delays were equalized or matched by appropriate internal delays. This statement holds for the noise components originating externally and for noise components generated internally by auditory nonlinearities. In contrast, the nonoverlapping of NπSo and NoSτ thresholds for larger delays (delays between 500 and 1000 μs or so) is taken as evidence that the external delays of the noise *were not matched* internally. This suggests that there is a *limitation* on the size of the ITD that can be matched internally. If that were true, then how does one explain the pattern of thresholds obtained with ITDs too large to be matched internally? Our hypothesis is that, for ITDs too large to be matched internally, detection is based on the interaural correlation coefficient. The interaural correlation coefficient is the value of the interaural correlation function at lag zero. Therefore, decisions based on it do not require equalization accomplished via the delay line. Our hypothesis differs from that made by Durlach (1972) and others, who assume that detection depends on the "best available internal delay" independent of whether that delay completely equalizes the external delay.

This line of argument leads us to look for two distinct regions in the data. In the region of "small" ITDs (those that
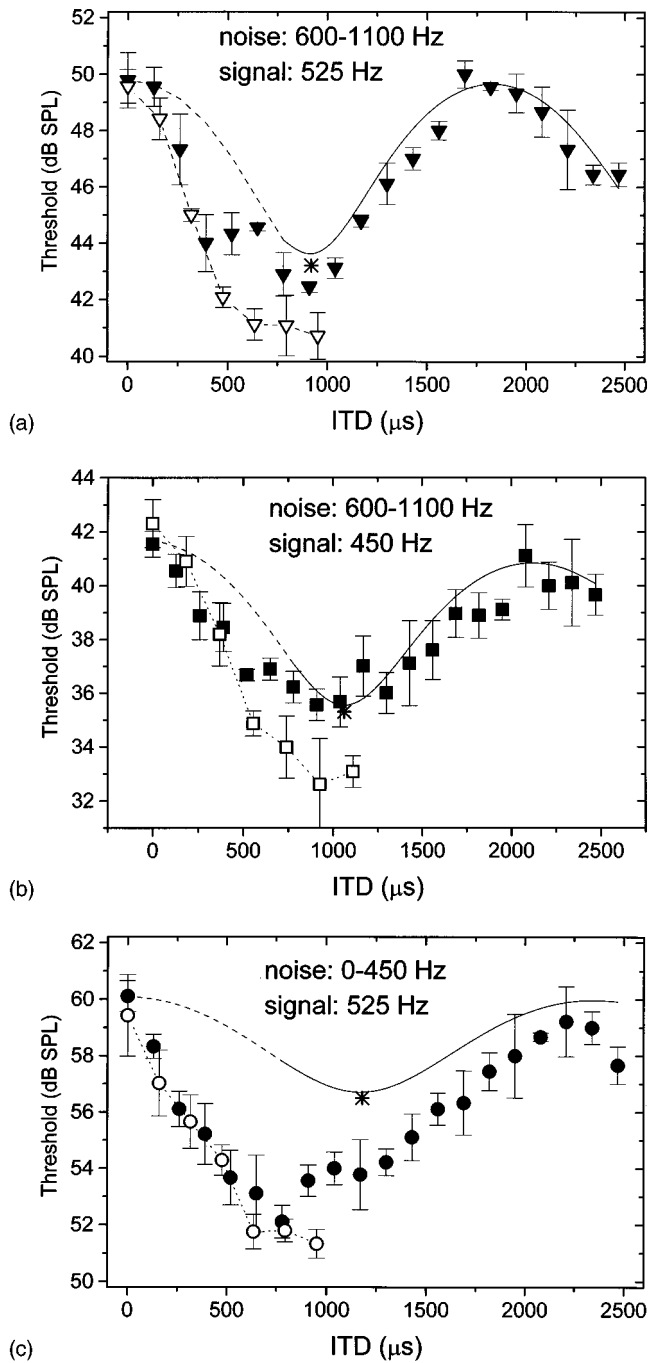
FIG. 3. Open symbols in panels (a)–(c) indicate NoSτ thresholds as a function of the ITD of the signal. Closed symbols in panels (a)–(c) indicate thresholds obtained in the corresponding spectral conditions using the NπSo configuration (these data are replotted from Fig. 1). Different panels correspond to different spectral conditions: the data in panels (a) and (b) were obtained with the spectral content of the noise ranging from 600 to 1100 Hz (and with signal frequencies of 525 and 450 Hz, respectively) and the data in panel (c) were obtained with the spectral content of the noise ranging from 0 to 450 Hz (and a signal frequency of 525 Hz). Solid lines indicate predictions based on the interaural correlation of an interaurally delayed noise stimulus for ITDs greater than 700 μs. The dashed lines represent extensions of the predictions to include ITDs less than 700 μs. NπSo thresholds are indicated by asterisks.

can be matched internally), the pattern of thresholds would reflect the frequency of the signal. In the region of "large" ITDs (those that *cannot* be matched internally), the pattern of thresholds would reflect the periodicity in the autocorrelation of the noise that is responsible for the masking.

We now evaluate whether NπSo thresholds obtained with ITDs presumably too large to be matched internally can be explained using the interaural correlation coefficient. We will begin with the data obtained when the frequency of the signal was *below* the spectral content of the noise. We assume that masking in this case was due to "on-frequency" aural distortion products and that the patterning of the data will reflect this. The methods used to evaluate this assumption were a bit complicated. We inspected the autocorrelation function of a 100-Hz-wide band of noise centered on the frequency the signal. The bandwidth of 100 Hz was chosen to approximate the bandwidth of noise at the output of a critical band at these low signal frequencies. The spectrum of the bands of noise contained a tilt (a spectral slope of 0.11 dB/Hz) favoring the higher frequencies. That value of spectral slope was determined by taking the 8-dB difference in detection threshold (obtained with an ITD of 0 μs) for the two signal frequencies placed spectrally below the noise and dividing that difference in threshold by the 75-Hz difference in the frequency of the signals. We made the reasonable assumption that the 8-dB difference in diotic (NoSo) thresholds for the two signal frequencies occurred because the noise power responsible for the masking differed by 8 dB across the two signal frequencies. This type of spectrum, "tilted" toward the higher frequencies, is consistent with the literature concerning aural distortion products (e.g., Goldstein, 1967; van der Heijden and Kohlrausch, 1995). Because of the spectral tilt, the autocorrelation function of the 100-Hz-wide band of noise, although centered on the frequency of the signal, is quasi-periodic with a frequency slightly *higher* than the frequency of the signal.

We evaluated the autocorrelation functions of the two noises for ITDs greater than 700 μs, a value chosen by considering all the data. The process involved recasting NπSo conditions into NρSo conditions, with ρ being the interaural correlation of noise stemming from aural distortion products. In order to do so, we had to obtain additional data using an NπSo stimulus configuration. These NπSo ($\rho = -1$) thresholds, in combination with the NoSo ($\rho = +1$) thresholds obtained in the main experiment, served as endpoints in the function relating NρSo detection thresholds to ρ. In order to obtain predictions of thresholds for intermediate values of ρ, we utilized the interpolation method recently described by van der Heijden and Trahiotis (1996).

The solid lines in panels (a) and (b) of Fig. 3 represent predictions obtained for ITDs $\geqslant 700$ μs using the interaural correlation *coefficient* of the tilted-spectrum bands of noise representing aural distortion products as discussed earlier. The reader is reminded that these predictions were made assuming that external ITDs were *not matched* internally. The correspondence between the predictions and the data appears to be quite good in both cases. When the signal frequency was 525 Hz [panel (a)], the amount of variance in the data accounted for by the predictions was 87%. When the signal frequency was 450 Hz [panel (b)], the amount of variance in the data accounted for by the predictions was 75%.

A corollary of our theoretical position is that extending

the predictions to ITDs *less* than 700 μs (the ITDs we have argued *are* internally matched) would reduce the amount of variance accounted for in the data. Indeed, as shown by the dashed line extensions to our predictions in Fig. 3, the predictions for the smaller ITDs would be quite poor. When we included those values of ITD in the analysis, the amount of variance accounted for decreased and was 67% and 65%, for the 525-Hz and the 450-Hz signals, respectively.

Overall, our analyses strongly suggest that aural distortion products are responsible for the masking that occurred when the frequency of the signal was *below* the spectral content of the noise. In our judgment, the predictions based on aural distortion products are remarkably good, especially when it is considered that the predictions were made by taking into account: only two behavioral thresholds and logical arguments concerning the properties of the aural distortion products assumed to be responsible for the masking.

As a check on the sensitivity of our analysis, we also investigated the autocorrelation function assuming a critical bandwidth of 200 Hz rather that 100 Hz. The amount of variance accounted for when the frequency of the signal was 525 Hz dropped to 72%. The amount of variance accounted for when the frequency of the signal was 450 Hz dropped to 61%. We take this as evidence that the first analysis, using the 100-Hz-wide critical bandwidth, was not a fortuitous success and that our data and methods have sufficient precision.

We now consider predictions for the case when the 525-Hz signal was spectrally *above* the components of the physical noise which ranged from 0 to 450 Hz. We investigated the interaural crosscorrelation of a 50-Hz-wide, rectangular, band of noise centered at 425 Hz. This band of noise was chosen because we assumed that masking was produced by frequencies at the upper edge of the noise and that such a band of noise would not be removed by an internal filter centered on 525 Hz, the signal frequency.

Predictions obtained using the general method described above are shown as the solid line in panel (c) of Fig. 3. Note that, in this case, the predicted thresholds are a poor fit to the data and are consistently *higher* than the obtained thresholds. In fact, using the mean as a predictor would provide a better fit to the data.

It is not the case that our assumption concerning which *frequencies* produced masking is responsible for the poor predictions obtained in this condition. On the contrary, the data obtained with ITDs greater than 700 μs are extremely well fit by single cosine functions having a frequency *within the upper region* of the band of noise. In fact, cosine functions having a frequency in the range of 420–450 Hz, the uppermost region of the noise, each accounted for more than 90% of the variance in the behavioral data. At the same time, a cosine function of 525 Hz, the frequency of the signal, accounted for less than 60% of the variance in the data collected with ITDs greater than 700 μs. Therefore, the inability to predict thresholds when the frequency of the signal was *above* the spectral content of the noise is *not* due to the periodicities in the data being somehow incompatible with the spectral region assumed to be responsible for the masking.

Our interpretation of the data is predicated on cancella-

tion of noise for the smaller delays that can be internally matched and on the use of the correlation coefficient (i.e., the correlation function at lag zero) for larger delays that cannot be internally matched. Of course, it is possible that binaural detection for ''in-between'' values of external delay may depend upon a combination of both modes of processing and/or a differential weighting of internal delays depending on their usefulness. In addition, our interpretations do not explicitly consider the potential use of ''slipped cycles'' for detection when external delays are large enough so that complete cancellation is impossible. As discussed by Rabiner *et al.* (1966), especially on pages 69 and 70, explanations of binaural detection data depending upon the use of slipped-cycle information involve a myriad of complex issues and data. At this time, we cannot provide an analysis of our data that incorporates, let alone resolves, the complex issues discussed by Rabiner *et al.* However, we believe that future data obtained utilizing very large delays (representing multiples of the periods of the signals) in our paradigm with masking produced by aural distortion products may permit the use of information in slipped cycles to be evaluated. Still, it appears to us that our analyses are an appropriate beginning toward the understanding of binaural detection data obtained under conditions where aural distortion products could be responsible for the masking.

We now present arguments that indicate that there is some other, unknown, factor that plays a role in binaural detection when the signal frequency is above the masking noise. Recall that, in order to make predictions for several values of interaural correlation via our interpolation method, we had to measure thresholds using an NπSo configuration. This was done for all three of our main experimental conditions. Those thresholds, which are represented by asterisks in panels (a)–(c) of Fig. 3, were *very close* to their NπSo counterparts when the frequency of the signals was *lower* than the spectral content of the noise [Fig. 3, panels (a) and (b)].

Note, however, that the NπSo threshold measured with the frequency of the signal *above* the spectral content of the masker [Fig. 3, panel (c)], is 3 dB *higher* than its NπSo counterpart. As a consequence, when the frequency of the signal was above the spectral content of the noise, the MLD between NπSo and NoSo conditions is slightly less than 4 dB. In contrast, the MLD between the equivalent NπSo conditions (i.e., an ITD of about 1000 μs) and the NoSo conditions is about 7 dB. This is a very important difference. *A priori*, one would expect that NπSo *thresholds*, for which the interaural correlation of the noise is -1, would be equal to, or lower than, thresholds obtained with any other values of interaural correlation of the masker. This means that the variations in the thresholds obtained when the frequency of the signal was *above* the spectrum of the noise cannot be explained solely in terms of the interaural correlation of the masker. This interpretation comes from relations among the data and does not entail assumptions concerning which spectral components contributed to the masking.

At this time, we have no explanation for the masking that occurred when the signal was spectrally above the noise and when the ITD of the noise was presumably too large to be equalized. In future investigations, we plan to determine

whether, and to what degree, binaural interference effects and binaural masking effects may combine or interact to determine detectability for signals placed spectrally above maskers and/or interferers. Binaural interference refers to degradations in the ability to detect or discriminate interaural differences in cases where masking effects can be ruled out. As discussed by Bernstein and Trahiotis (1995), binaural interference effects are often asymmetric in that low-frequency interferers affect high-frequency targets more than high-frequency interferers affect low-frequency targets. At this time, it appears not too far-fetched to speculate that noises containing large ITDs cannot be equalized and, therefore, cannot be canceled. Consequently, they may remain to affect detectability via binaural interference.

In summary, we have presented data suggesting that aural distortion products that are evoked by a band of noise have the ability to produce binaural masking of tonal signals having a frequency *below* the spectral content of the noise. The detectability of such signals is well accounted for by considering the expected interaural correlation of aural distortion products evoked by interaurally delayed noise. We conclude that aural distortion products can produce binaural as well monaural masking effects (e.g., van der Heijden and Kohlrausch, 1995). On the other hand, data obtained with tonal signals having a frequency *above* the spectral content of the noise are not satisfactorily accounted for by considering the interaural correlation of the noise. It appears that another factor, perhaps binaural interference, limits binaural detectability for signals placed spectrally above masking noise.

ACKNOWLEDGMENTS

Bernstein, L. R., and Trahiotis, C. (**1995**). ''Binaural spectral interference in detection and discrimination paradigms,'' in *Advances in Hearing Research: Proceedings of the 10th International Symposium on Hearing*, edited by G. A. Manley, G. M. Klump, C. Koppl, H. Fastl, and H. Oekinghaus (World Scientific, Singapore).

Bilger, R. C., and Hirsch, I. J. (**1956**). ''Masking of tones by bands of noise,'' J. Acoust. Soc. Am. **28**, 623–630.

Durlach, N. I. (**1963**). ''Equalization and cancellation theory of binaural masking-level differences,'' J. Acoust. Soc. Am. **35**, 1206–1218.

Durlach, N. I. (**1972**). ''Binaural signal detection: Equalization and cancellation theory,'' in *Foundations of Modern Auditory Theory, Volume II*, edited by J. V. Tobias (Academic, New York), pp. 365–466.

Goldstein, J. L. (**1967**). ''Aural combination tones,'' J. Acoust. Soc. Am. **41**, 676–689.

Hall, J. W., Tyler, R. S., and Fernandez, M. A. (**1983**). ''Monaural and binaural auditory frequency selectivity resolution measured using band-limited noise and notched-noise masking,'' J. Acoust. Soc. Am. **73**, 894–898.

Langford, T. L., and Jeffress, L. A. (**1964**). ''Effect of noise crosscorrelation on binaural signal detection,'' J. Acoust. Soc. Am. **36**, 1455–1458.

Levitt, H. (**1971**). ''Transformed up-down methods in psychoacoustics,'' J. Acoust. Soc. Am. **49**, 467–477.

McFadden, D., Russell, W. E., and Pulliam, K. A. (**1972**). ''Monaural and binaural masking patterns for a low-frequency tone,'' J. Acoust. Soc. Am. **51**, 534–543.

Rabiner, L. R., Laurence, C. L., and Durlach, N. I. (**1966**). ''Further results on binaural unmasking and the EC model,'' J. Acoust. Soc. Am. **40**, 62–70.

van der Heijden, M., and Kohlrausch, A. (**1995**). ''The role of distortion products in masking by single bands of noise,'' J. Acoust. Soc. Am. **98**, 3125–3134.

van der Heijden, M., and Trahiotis, C. (**1996**). ''A new way to account for binaural detection as a function of interaural noise correlation,'' J. Acoust. Soc. Am. (accepted for publication).